Evaluation, Modeling, and Analysis of Shipping Container Building Structures

THESIS

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ABSTRACT

Currently, guidelines for safely using shipping containers for building applications do not exist. The shipping container's structural integrity, modification properties, foundation limits, building code regulations, and reinforcing limits are mostly unknown. As a result, this research begins the investigation of shipping containers' structural limitations thus aiding the development of container building construction and design requirements.

The main research objective is to develop structural guidelines for the International Organization for Standardization (ISO) shipping containers used for non-shipping applications. This paper provides insight into the ISO shipping container's structural strength which is further investigated using finite element computer modeling. The finite element analysis shows how both modified and unmodified container models respond under given loading scenarios. The loading scenarios incorporate the effect of gravity and lateral loading, and the computer simulations demonstrate the effectiveness of the container walls or roof to resist the loads. Structural engineering considerations, foundation and connection design, and future research suggestions for using shipping containers in building applications are presented.

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CHAPTER 1

INTRODUCTION

1.1 Overview

The original intent for steel containers to ship items around the world has changed considerably. Today, shipping containers are used for housing, shelters, military structures, hospitals, stores, and even portable restaurants. Many of the shipping containers used for non-shipping applications are modified from their original design. Cut outs for windows, doors, steps, and other modifications are incorporated into the shipping container. Companies and manufacturers design and install these modifications, but their designs for safely modifying shipping containers are not publicly available.

There is limited research and literature describing the economics, environmental impacts, and feasibility of using shipping containers for applications other than transporting goods. Currently, guidelines for safely using shipping containers for building applications do not exist. The shipping container's structural integrity, modification properties, foundation requirements, building code regulations, and reinforcing limits are mostly unknown. As a result, this research begins the investigation of shipping containers' structural limitations thus aiding future documents for container building construction and design requirements.

1.2 Scope and Objectives

The scope of this graduate thesis encompassed an in-depth literature review giving insight into the ISO shipping container's structural strength which was further investigated using finite element computer modeling. The finite element analysis of the container was performed under gravity loads and other loading scenarios to which the container may be subjected. The research analyzed how both modified and unmodified containers responded under given loading scenarios. Structural engineering considerations, foundation and connection design, and future research suggestions for using shipping containers in building applications were presented.

The main research objective was to develop structural guidelines for the International Organization for Standardization (ISO) shipping containers used for non-shipping applications. A comprehensive overview of most literature applicable to shipping container buildings was developed. The literature included container documents presenting general information, standards, engineering building codes, industry information, and structural testing on shipping containers. Foundations, connections, and reinforcement options for shipping container buildings are also discussed. The structural response and limitations of shipping containers under various loading conditions and modifications are analyzed. The analysis is conducted using finite element computer simulations, container standards, and container industry data. Future considerations for shipping container research are presented as well.

1.3 Project Summary and Organization

The research reviewed container documents and information applicable for shipping container buildings. Multiple shipping container tables created presented classifications, structural considerations, and dimensions. Engineering building codes pertaining to shipping container housing were discussed, and container industry professionals were consulted. Foundations, connections, and reinforcing guidelines for shipping container buildings were discussed as well. Multiple finite element computer models of shipping containers were created and analyzed using the computer programs SolidWorks (2011), Hypermesh (2009), and Abaqus/CAE (2010). An optimized container model was modified into seven different container configurations. Five different loading scenario simulations were applied to each of the modified container models and analyzed, and comparisons between container modifications were discussed and presented.

Chapter 1 discusses a brief overview of the research. Chapter 2 presents shipping container background information by reviewing literature from industry, military, and academia. Chapter 3 discusses the standards used for creating, operating, and maintaining shipping containers. Chapter 4 discusses engineering codes and industry considerations for shipping containers. Chapter 5 discusses foundations, connections, and reinforcing options for shipping container buildings. Chapter 6 presents multiple shipping container computer model simulations tested for accuracy and efficiency. Chapter 7 performs computer simulations for an optimized shipping container computer model and modifies it. The modified container models are tested under different loading scenarios and

analyzed. Chapter 8 presents the conclusion to the research and future research considerations.

CHAPTER 2

BACKGROUND INFORMATION

2.1 Overview

Published information on shipping containers used for non-shipping applications is rare, and published data needed for structural modeling and analysis of shipping containers is even more difficult to find. Many of the available publications do not discuss the structural strength and response of shipping containers under abnormal loading scenarios or modifications. This section gives an overview of publications on shipping containers, and focuses on shipping containers used for building purposes.

2.2 General Container Information

The International Organization for Standardization (ISO) and the International Convention for Safe Containers (CSC) created documents which dictate shipping containers' specifications, structural strengths, serviceability, and applications. Nearly every globally used shipping container conforms to these documents. Intermodal freight container, intermodal container, freight container, and shipping container are all terms used unanimously to describe a CSC certified container. ISO shipping container, ISO freight container, and ISO container are terms used unanimously to describe an ISO

certified container. Other shipping container terms used for building applications are: intermodal steel building unit (ISBU) and containerized housing unit (CHU). The CSC and ISO documents are described in greater detail in Chapter 3.

The United States military discusses CSC and ISO certified shipping containers in the document titled: Joint Tactics, Techniques, and Procedures for Use of Intermodal Containers in Joint Operations (Joint, 1997). This publication describes, “techniques and procedures for effective and efficient use of intermodal containers and systems to deploy, sustain, and redeploy forces” (Joint, 1997). The United States military requires shipping containers to conform to American National Standards Institute (ANSI) and ISO specifications (Joint, 1997). US federal standards for intermodal containers follow the guidelines from ISO Documents: 668, 830, 1161, 1496-1, 1496-2, 1496-3, 1496-4, 1496-5, 1496-6, 2308, 3874, and 6346 (Joint, 1997). This publication reviews freight container details from the ISO publications, but most of the items presented are directly applicable for military uses and not this research study.

Unaffiliated with ISO or container standards, Levinson (2006) discusses intermodal and global transportation of goods. He presents the history of the shipping industry, how the shipping container came to be, and how the global shipping industry was revolutionized overnight. The book is not related to this research directly, but it gives interesting insight to the global impact shipping containers have.

2.3 Containers Used as Buildings

Kotnik (2009) presents examples of shipping containers used as structural components of a building or dwelling. Containers are attractive for architects because they are: prefabricated, compact, sturdy, weather-resistant, and potentially mobile. Architects see the containers as large building blocks stating, “there are unlimited spatial combinations they can be combined into”. Kotnik (2009) briefly touches on constructing and modifying shipping containers, but did not describe any practical procedure or guidance.

There are several books similar to Kotnik (2009) where interesting building projects using shipping containers are presented. However additional reinforcement is provided to the containers in most cases, because the container’s structural strength is unknown when modified. Figure 2.1 shows an example of an impractical shipping container building. Although aesthetics are important for architects, shipping containers cannot be viewed as building blocks if efficiency and economics are driving the project. The projects described in Kotnik (2009) and other architecturally driven container building books are not applicable to this research, because they typically do not take into account structural considerations.

Sawyers (2005) produced a non-architecturally driven container construction book discussing the process of acquiring, transporting, and installing shipping containers. He also discusses container foundation options, building plans, layouts, modifications, and insulation options. Large amounts of detail and information are provided for shipping container shelter options. However, his guides for foundation, modification, and

construction designs rely on rule of thumb as opposed to structural engineering principals and structural details. His ideas for different foundation options are discussed and analyzed in Chapter 5.

A lengthy dissertation written by Smith (2006) at the University of Brighton covers many aspects for using shipping containers for non-shipping purposes. He gives examples of conceptual container work and touches briefly on actual buildings using ISO shipping containers. Although the research discusses some important ideas, most of the information is not applicable for this research.

Gorgolewski et al. (2001) authored one of the few books to discuss structural design considerations for a small box shaped structures. Structural design considerations such as loadings, design orientations, limitations, and connections are presented. The focus of the book is to produce a finished, fully operational building. Cladding, roofing, insulation, finishes, benefits of modular housing, sustainable design suggestions, and architectural considerations are all discussed as well. Unfortunately, the book is meant for prefabricated modular units and building codes used in the United Kingdom. Since this research is focusing on ISO containers, most of the applications presented were not applicable. The methodologies for selecting loading conditions and structural considerations are taken into account.

The Joint (1997) publication is one of the few publications to mention the use of ISO containers for tactical shelters and facilities. The report describes the benefits of using containers as Mobile Facilities (MFs) and ISO shelters for the United States military. These MFs and ISO shelters are pre-fabricated and then shipped to the end user.

Figure 2.2 shows a container structure used for the military. However, the focus of this research is to modify existing standard ISO containers in the field for specific uses, not having pre-fabricated modifications (Joint, 1997).

The American Society for Testing and Materials (ASTM) created pre-fabricated containers documents: Specification for Engineering and Design Criteria for Rigid Wall Relocatable Structures and Standard Specification for Shelter, Tactical, Nonexpandable (ASTM E 1925, 2001 and ASTM E 1976, 2004). These ASTM documents, referencing ISO standards, present structural standards for pre-fabricated, modified containers used in military applications. ASTM discusses scenarios which could be applied to the military container including: temperature, flooding, and structural tests. The actual tests performed on the prefabricated, modified containers are not used in this research, but some of the loading scenarios are considered in Chapter 7.

2.4 Structural Testing on Containers

Most of the recent documents involving actual structural testing on ISO containers use blast loading scenarios. While this research is not investigating blast loading scenarios, the information provided in this chapter is relevant and important to structurally define and evaluate performance of the ISO container. It is also most likely the only information publicly available involving modifications and testing of full scale shipping containers.

Genelin et al. (2009) presented a full scale testing of an ISO container under blast loading conditions. The research was conducted to compare a typical 20 ft ISO container

to a Steel Encased Foam Core Panels (SEFCP) system applied to an ISO container steel frame. Three blast experiments were conducted and compared with analytical models for the SEFCP structure and ISO container. The standoff distances, the charge of the blast, and other details were not included in the report. The shipping container deflected inward and became rippled but was not damaged further. The analytical data was not used to compare or investigate the details of the structural response.

Another blast loading study conducted on an actual 20 ft ISO container was a two phase experiment by Borvik et al. (2011). Similar to Genelin et al. (2009), this experiment discussed fortification options of ISO shipping containers. Most of the research in these articles discussed the protective system, but a standard unprotected ISO container was modeled using a finite element (FE) program and analyzed. Up until this publication, published FE modeling of an ISO container was difficult to locate.

Borvik and his colleagues discussed the finite element modeling of the container, including assumptions and simplifications. The container FE model did not contain corner fittings or doors at one end, and the container was fixed to the ground to simulate a more severe scenario during a blast loading. For the FE model, all the components of the container were tied together at first. Independent of the amount of damage or deformation, all the components stuck together and failure in the connections was not allowed (Borvik et al., 2011). For the same blast loading scenario, more realistic contact surfaces were applied where failure between the contact of container parts was allowed. For example, when the components of the container separated from each other at a given load, this was modeled.

The conclusion of the research was the FE model of the 20 ft ISO container would be severely damaged with a 48 kPa blast pressure. The actual container with five pressure gauges, was subjected to a blast loading of 4000 kg of TNT at a standoff distance of 120 m. The actual container when subjected to the blast loading had severe plastic deformations in many of its members, but none of the components fractured.

Researchers at the Air Force Research Laboratory (AFRL) and University of Missouri-Columbia also conducted large scale testing on ISO shipping containers subjected to blast loading. Similar to Borvik's research, Genelin and Salim (2010) investigated lightweight wall systems for ISO containers and compared their performance to an unprotected, standard ISO container under blast loading. They performed a blast loading test on nine ISO containers stacked three high by three long. Their research was one of the first to discuss connections between the containers using welding and twist lock mechanisms, adding windows with reinforcing, and creating various stud wall configurations. Unfortunately, the blast loading values and standoff distances were excluded from the published research data, and flying debris damage was mainly focused on.

Figure 2.1: Impractical Container Structure (Kotnik, 2009).

Figure 2.2: Barracks Container Structure During Construction (Hermann, 2007).

CHAPTER 3

SHIPPING CONTAINER STANDARDS

3.1 Introduction

The International Organization for Standardization (ISO) Technical Committee (TC), ISO/TC 104, develops and maintains ISO freight container standards. The American National Standards Institute (ANSI) supports the United States to participate in the ISO/TC104 to develop guidelines and specifications for intermodal containers with USA's interest in mind.

The U.S. federal law requires existing and new containers to meet Convention for Safe Containers (CSC) standards. The International Maritime Organization (IMO) develops and maintains the CSC standards. The CSC standards came before ISO, and many of ISO's container standards are taken from the CSC standards. It is important to note that the IMO and ISO are not affiliated. ISO is allowed to comment on IMO's decisions regarding CSC standards, but does not have a vote. ANSI and IMO are not affiliated either.

Chapter 3 describes and compares all the ISO and CSC standards applicable for shipping containers. If a container meets all the ISO standards listed in this chapter, the container will meet all the CSC standards but not vice-versa. Nearly every shipping

container manufacturer has adopted the ISO container standards in order to be competitive and compatible worldwide. This chapter investigates all CSC standards, shipping container manufacturer data, and ISO container standards 668, 830, 6346, 1496-1, 1496-2, 1496-3, 1496-4, 1496-5, 1161 2308, and 3874.

3.2 ISO 668: Classification, Dimensions, and Ratings

ISO 668 defines the shipping container's dimensions, tolerances, and weight. A freight container is, "an article of transport equipment of a permanent character and accordingly strong enough to be suitable for repeated use...fitted with devices permitting its ready handling, particularly its transfer from one mode of transport to another" (ISO 668, 1995).

In Appendix A, Table A.1 displays the external length, width, height, and rating values for multiple types of ISO containers, Table A.2 displays internal and minimum door opening dimensions for multiple types of ISO containers, and Table A.3 displays center to center distances between corner fittings and diagonal tolerances for each container type. Table A.1, Table A.2, and Table A.3 all reference to Figure A.1, and Figure A.1 displays the characters used to describe each dimension of the ISO container. This research uses the ISO 668 standard for all container dimensions, tolerances, and ratings.

3.3 ISO 830: Vocabulary

ISO 830 describes the terminology associated with all the ISO container standards, and ISO 830 defines container components and container vocabulary. This research uses the ISO 830 terminology and container vocabulary when necessary (ISO 830, 1999). The most important terms used in this research are: payload (P) which is the maximum permitted mass in a container, rating (R) value defined as “the gross mass of a container which is both the maximum mass for operation and the minimum mass for testing”, and tare mass (T) which is the mass of an empty container (ISO 830, 1999). The payload (P) is the difference between the rating (R) and tare values (T).

3.4 CSC & ISO 6346: Coding, Identification, and Marking

ISO 6346 gives information for identifying an ISO container’s dimensional properties, applications, and ownership using external markings on the container. Every ISO freight container must have an owner code (three letters) followed by an equipment category (one letter), a serial number (six numbers), a check digit (single number in a square), and a size and type code (combination of four letters and numbers). These identification markings can be displayed in various locations and oriented differently on the container (ISO 6346, 1995). Figure 3.1 shows an example of each marking on a 20 ft long container.

The most important identification markings on the container are the size and type code markings (combination of four letters and numbers shown in Figure 3.1). These four characters describe the length, height, width, and use of the container. The first two

characters (size code) describe the dimensions, and the last two characters (type code) describe the use of the container. Tables A.4 and A.5 in Appendix A define the characters for the size and type code marking. Using the size and type code markings, Table A.6 in Appendix A presents which ISO containers can stack on top of other ISO containers with corner posts aligned. The type code (last two characters) does not usually govern the containers stacking compatibility.

CSC also has an identification system which uses a Safety Approval Plate usually applied to one of the container's doors. CSC goes into great detail regarding administrative guides and procedures for the Safety Approval Plate (CSC, 1996). The Safety Approval Plate shows: country of approval, date of manufacture, manufacturer's identification number, maximum operating gross weight, allowable stacking load, transverse racking test force, potentially sidewall and endwall strengths, maintenance examinations, and one door off container strengths (if applicable).

3.5 CSC & ISO 1496-1, 1496-2, 1496-3, 1496-4, & 1496-5: Specification and Testing

ISO 1496 contains five parts which describe a series of structural tests all ISO containers must pass in order to be in operation. The required tests are the only source of information regarding the container's structural strength characteristics. Unfortunately, manufacturer test data is not available, and container manufacturers do not discuss the tests presented in ISO 1496. Without container manufacturers disclosing their test data, it is impossible to verify an ISO shipping container's structural strength consistently and accurately. Container manufactures have documentation describing their process for

testing the containers following ISO 1496's guidelines, but many of the manufacturers are using old editions of ISO 1496 for testing procedures. Container failure is a rare occurrence, and the research assumes the containers are robust and conservatively designed.

Table 3.1 displays the types of containers considered for each part of ISO 1496. CSC also describes many of the test procedures which ISO 1496 adopted as their own (CSC, 1996). Whereas the ISO 1496 documents only pertain to certain containers, CSC is applied to all containers which could pass the structural tests. The structural strength highlights for 20 ft and 40 ft containers from ISO 1496-1 and CSC are presented in Table A.7 with structural considerations included. Each structural test is described and diagrams with applied forces are also presented in Table A.7.

3.6 ISO 1161: Corner Fittings Specification

Every ISO shipping container must have corner fittings conforming to the guidelines presented in ISO 1161. The corner fitting's terminology, dimensions, and structural strengths are represented (ISO 1161, 1984). Guidelines for twist locks and securing to vehicles are presented as well. With similar skepticism to ISO 1496 tests, the structural tests conducted on the corner fittings are impossible to confirm without full scale testing. This research uses the corner fitting dimensions and suggestions presented in ISO 1161.

3.7 ISO 2308 and 3874: Handling and Securing

ISO 2308 and especially ISO 3874 describe methods for handling and securing ISO shipping containers. Specific lifting methods, lifting devices, securing procedures, and securing devices are all described in great detail in ISO 3874 (ISO 3874, 1997). Many of the ISO container connecting devices have structural limits presented throughout ISO 3874 Amendment 1 (ISO 3874: Amd. 1, 2000). Although this specific research does not discuss detailed container installations, ISO 2308 and 3874 describe most procedures for transporting an ISO shipping container. Chapter 5 discusses the structural properties of ISO shipping container connecting devices presented in ISO 3874.

3.8 Master Container Document

A fairly comprehensive container database is compiled in Appendix B. Eleven entities (container manufacturers and shipping lines) are referenced to determine shipping container types, dimensions, weights, and compressive forces. Many of the values are averaged from multiple shipping container manufacturers, and the goal of this database is to show properties of most shipping containers currently produced.

Figure 3.1: ISO 6346 Container Character Definitions.

	ISO 1496-1	ISO 1496-2	ISO 1496-3	ISO 1496-4	ISO 1496-5
Container Type	General, Specific purpose, Closed, Vented/ventilated, Open top	Thermal	Tank, Bulk, Pressurized	Bulk, Non-pressurized (box and hopper types)	Platforms
Type Codes Considered (Table A.5)	00 to 19, 50 to 59, G0 to G3, V0, V2, V4, U0 to U3	30 to 49, H0 to H2, R0, R1	70 to 79, 85 to 89, T0 to T6, T8, T9	20 to 24, 80 to 84, B0	60 to 69, P0 to P5

Table 3.1: Container Types for each ISO 1496 part (ISO 1496-2, 1996).

CHAPTER 4

ENGINEERING CODES AND CONSIDERATIONS FOR SHIPPING CONTAINERS

4.1 Introduction

In order to create buildings using shipping containers, various engineering codes need to be followed and referenced. Many considerations used for regular construction projects share similar procedures when constructing with shipping containers. Chapter 4 describes the engineering codes and considerations that can be used for shipping container building construction.

4.2 Engineering Codes Applicable to Container Building Construction

An unmodified ISO container must meet all ISO standard criteria presented in previous chapters. An unmodified shipping container used for global transportation will most likely meet CSC requirements. Once the container is modified, then different building codes and guidelines must be used depending on the container's application.

Military applications for modified containers are either ISO shelters or mobile facilities (MF). The containers are modified to have different wall, roof, and floor materials, and the ISO shelters and MF types meet ISO design standards (Joint, 1997 and Department of Defense, 2002). All the military containers also meet ASTM E 1925

(2001) and ASTM E 1976 (2004) guidelines, but it is unclear if the modified military containers must be CSC certified.

If a container used for global shipping is modified, then it must be recertified to all CSC requirements and be structurally re-tested (CSC, 1996). The governing codes for constructing buildings or shelters with modified shipping containers are the local building codes which typically refer to the International Building Code (IBC, 2011).

IBC is an international building code which describes every facet to constructing a structure. In order to design a structure with shipping containers, generally the IBC code needs to be followed in order to meet local building standards. IBC references many structural engineering resources to compile a comprehensive construction guide. These structural engineering resources include concrete building code (ACI 318, 2008) and steel design manual (AISC, 2011).

ACI 318 (2008) is the governing engineering code involving reinforced concrete. Concrete foundation design and considerations in this research reference ACI 318. Foundation design requires a detailed overview of soil conditions and information found in Cudato (2001), IBC (2011), and NAVFAC DM - 7.2 (1986). The public document created by the Department of the Navy, NAVFAC DM - 7.2 (1986), presents detailed soil information and examples used for foundation design. Cudato (2001) ties in many building codes throughout the world to develop a comprehensive guideline for soil classification, foundation design, and geotechnical considerations. This research uses Cudato (2001), IBC (2011), and NAVFAC DM-7.02 (1986) geotechnical guidelines when designing the foundations for the containers. Also, AISC is the primary engineering

building code for steel structures (AISC, 2011). This research references AISC steel construction manual when describing and designing reinforcing and foundation options for shipping containers. The American Society of Civil Engineers (ASCE) produces an engineering code known as ASCE 7 (2010). ASCE 7 describes different loading scenarios and safety factors engineers must use when designing structures.

The American Iron and Steel Institute (AISI) produces a document, which incorporates cold formed steel design considerations (AISI, 2008). The bottom and top side rails and other components of the shipping container are cold formed steel which may require different loading conditions other than those specified in ASCE 7.

4.3 Shipping Container Construction Considerations

Naef (2011), Director of Intermodal Steel Building Units (ISBU) and Container Homes Association, provided valuable insight for design and evaluation of shipping containers used in real world building construction. Every building situation involving shipping containers was unique, but he has developed some methodologies to make the construction process more efficient.

Naef (2011) recommended using the term, ISBU based, as opposed to shipping container home. When an ISBU is used, ensure the container's interior, exterior, and roofing meet the local engineering codes. Naef (2011) stated, "Nothing I've seen submitted for a normal home or office with plans and local licensed engineer signing off, has ever met rejection. At least, no more difficult than a normal project." Naef (2011) also discussed how foundation designs, insulation, fire code, floor toxic fumes, and

prefabricated units all presented unique issues with shipping containers used for building purposes.

Runkle (2011) at Runkle Consulting, Inc. is one of the few structural engineers who actually designs and constructs shipping container homes. He recommended using finite element computer programs to analyze the containers and also mentioned cold formed steel knowledge is important. The containers are very weak when the side walls are removed, and the gap produced between containers when stacked is very difficult to fill. Runkle also described the cost of using an ISO shipping container for a single home is more expensive than traditional construction methods and will remain a niche market. He believes the main usage for shipping container buildings would be for mining, disaster, and on-site construction project housing.

4.4 Damaged Shipping Container Considerations

CSC and the Department of Defense create documents which describe the shipping container's ability to operate based on damages. "The subsequent maintenance of a safety-approved container is the responsibility of the owner, who is required to have the container periodically examined," (CSC, 1996). New containers must be examined within five years of date of manufacture and every 30 months from there on (CSC, 1996).

The Department of Defense Handbook (2002) gives insight to container durability and functionality when damaged, and the inspection guide follows ISO and CSC standards. The container inspection guide goes into great detail presenting container components and definitions for many types of shipping containers including military

tactical shelters. Diagrams of damages, repairs, and container inspections are also presented (Department of Defense, 2002). Many images of ISO containers found on the internet are taken from this document.

Table A.8 presents container retrofit information and damage individual ISO container components can have to be considered safe for operation. The component of an ISO container is considered failed if a value in the chart for Table A.8 is met. If a component is considered failed, the container should not be used until the component is fixed.

CSC also describes structural deficiencies for each component of a shipping container in Table A.9 which encompasses all shipping containers. The values from CSC are far less conservative than the values presented in Table A.8. Sawyers (2005) also briefly mentioned container damage considerations which are very similar to CSC and the Department of Defense documents. This research does not directly consider the container damage suggestions, because undamaged containers are modeled and analyzed.

CHAPTER 5

SHIPPING CONTAINER FOUNDATIONS, CONNECTIONS, AND REINFORCEMENT

5.1 Introduction

Shipping container structures are typically light weight and usually do not require strong foundations, and the shipping containers themselves are very structurally stable and provide an excellent structural building component. This chapter describes soil types, foundation options, connections, reinforcing, and design methodologies for ISO shipping container applications. This chapter provides a starting point to develop foundation design assumptions for container structures, but further investigations are necessary.

5.2 Soil Conditions and Geotechnical Information

In order to design the foundation for the structure, the soil's allowable bearing pressure needs to be determined. The allowable bearing pressure of the soil is, "the largest bearing pressure that satisfies both bearing capacity and settlement criteria," (Cudato, 2001). Typically, a geotechnical investigation is necessary to determine the soil's attributes and allowable bearing pressure. If a geotechnical investigation is unavailable, suggested allowable bearing pressures for different soil types are presented in IBC (2011), NAVFAC DM-7.02 (1986), and Cudato (2001). Table 5.1 compares the

allowable soil bearing pressure for shallow footings recommended in different building codes. Until further investigation can be completed, the allowable bearing pressures for soils presented in IBC 2011 should be used, shown in Table 5.2.

Soils are subjected to many scenarios which can alter the soil's attributes and can cause structural damage to the foundations. Frost heave, expansive soils, slopes, bedrock, landslides, collapsible soils, liquefaction, flood zones, and compacted fills all potentially could damage the structure. Further research is needed in order to include these scenarios into the shipping container foundation design.

5.3 Types of Foundations

There are a large variety of foundations to use for a structure. The specific type of foundation depends on many factors such as location, soil conditions, and type of structure to be supported. Shallow foundations contain spread footings and mats. Spread footings are a reinforced concrete enlargement at the bottom of a column in a structure. Spread footings are ideal for small to medium size structures with moderate to good soil conditions, are very economical, easy to construct, and have a variety of shapes and sizes. (Cudato, 2001).

Mat foundations are enlarged spread footings encompassing the building footprint (Cudato, 2001). Mats are used when spread footings would cover more than 50 percent of the building footprint, when unpredictable settlements may occur, if uplift forces are too large for regular spread footings, and if the ground water table is above the footing

(Cudato, 2001). For more complex soil types or heavier structures, deep foundations are typically used.

Deep foundations are used when the surface soils are too weak to build on, the spread footing area exceeds one-third the building's footprint, the soils are subject to scour and potential flooding, and large uplift or lateral load capacity is needed (Cudato, 2001). Deep foundations contain a variety of types, however this research only discusses piles.

Piles are long columns made of concrete, steel, or timber, and can extend well over 20 ft into the soil. Piles potentially could be used in soft soils or flooded areas to elevate the container structures and provide structural stability. Unfortunately, pile foundations typically require a large machine to drive them into the soil which increases installation time and cost.

Most of the structures created from shipping containers use either concrete spread footings or a mat foundation. Also, concrete masonry blocks and bricks potentially can be used for foundations as shown in Figure 5.1. There are other options available and may be used depending on the building's site characteristics. Gorgolewski et al. (2001) suggests strip (connected spread footings), pad (mat), or pile foundations with use of base plate. However Gorgolewski et al. (2001) did not discuss connection details between the container and the foundation. Sawyers (2005) recommended using wood beam footings (similar to spread footings), weld-on jack stands, concrete foundations, concrete footings, and helical piles. The Army and Marine ISO Shelters use built-in jacks to allow adaptation to a variety of terrain conditions. The research seeks to provide exposure to

various foundation options for different container structure applications, but foundation designs for specific container configurations on various soils are not presented. In this research it is assumed the container structure is fixed at the at the support locations.

5.4 Loads Acting On Container Foundations

Table A.7 displays the maximum loads ISO states a 20 ft ISO shipping container can safely withstand. Using these loading scenarios for design loads, it gives a starting point for determining the maximum loads a container foundation needs to withstand. Different soils and locations may present unique loading scenarios not discussed in this research.

5.5 Connection Options for Shipping Containers

Once the foundation for a shipping container structure is established, the container must be connected to the foundation. A common connection method attaches a container to an appropriately designed steel base plate with welds as shown in Figure 5.2. The underside of the base plate has reinforcing bars (anchor bolts) of varying lengths. The base plate's anchor bolts are welded to the underside of the plate and are cast into the concrete foundations or grout while it is still wet. Once the concrete or grout is hardened, the base plate is anchored into the foundations. AISC (2011) Section J and ACI 318 (2008) Appendix D describe the design procedure for base plates with anchoring.

There are multiple options for connecting containers to other containers or transporting devices (ISO 3874: Amd.1, 2000). The connection devices lock the

containers together by attaching through the top or bottom openings on the corner fittings. Twist locks and latchlocks are connection devices securing two containers at the corner fittings during stacking, transporting, or lifting empty container situations. Stacking fittings or stacking cones secure containers only horizontally during stacking or transporting and are always used in junction with other securing devices. The stacking fitting is similar to the twistlocks and latch locks, but it does not rotate to lock anything in place. Table 5.3 displays the structural strengths of each container connection device, and lashing rods are not discussed in this research.

5.6 Reinforcement

If a modified container structure was to be re-transported using typical transportation methods, it would have to meet CSC and possibly ISO structural test requirements (CSC, 1996 and ISO 1496-1, 1990). This is especially important for containers used in military and transportation applications (CSC, 1996). The research aimed to provide maximum allowable loading scenarios for given modifications without using reinforcing, and future considerations for reinforcement are discussed in Chapter 8.

Navy Facilities Engineering Command (NAVFAC DM-7.02 , 1986)			International Building Code (IBC, 2011)	Uniform Building Code (ICBO, 1997)
Type of Bearing Material	Consistency In Place	q _a	q _a	q _a
Massive crystalline igneous and metamorphic rock: granite, diorite, basalt, gneiss, thoroughly cemented conglomerate (sound condition allows minor cracks).	Hard, sound rock	160000	12000	4000-12000
Foliated metamorphic rock: slate, schist (sound condition allows minor cracks).	Medium hard sound rock	70000	12000	4000-12000
Sedimentary rock; hard cemented shales, siltstone, sandstone, limestone without cavities.	Medium hard sound rock	40000	4000	2000-6000
Weathered or broken bed rock of any kind except highly argillaceous rock (shale). RQD less than 25.	Soft Rock	20000	4000	2000-6000
Compaction shale or other highly argillaceous rock in sound condition	Soft Rock	20000	4000	2000-6000
Well graded mixture of fine and coarse-grained soil: glacial till, hardpan, boulder clay (GW-GC, GC, SC).	Very compact	20000	3000	2000-6000

Continued

Table 5.1: Allowable Bearing Pressures for Various Building Codes.

Table 5.1 Continued:

Gravel, gravel-sand mixtures, boulder gravel mixtures (SW, SP).	Very Compact	14000	3000	2000-6000
	Medium to Compact	10000		
	Loose	6000		
Coarse to medium sand, sand with little gravel (SW, SP).	Very Compact	8000	2000	1500-4500
	Medium to Compact	6000		
	Loose	3000		
Fine to medium sand, silty or clayey medium to coarse sand (SW, SM, SC).	Very Compact	6000	2000	1500-4500
	Medium to Compact	5000		
	Loose	3000		
Homogeneous inorganic clay, sandy or silty clay (CL, CH)	Very stiff to hard	8000	1500	1000-3000
	Medium to stiff	4000		
	Soft	1000		
Inorganic silt, sandy or clayey silt, varied silt-clay-fine sand	Very stiff to hard	6000	1500	1000-3000
	Medium to stiff	3000		
	Soft	1000		
	*q _a = Allowable Bearing Pressure (lb/ft ²)			

International Building Code (IBC, 2011)	
Type of Bearing Material	Allowable Bearing Pressure (lb/ ft²)
Crystalline bedrock	12000
Sedimentary and foliated rock	4000
Sandy gravel and/or gravel (GW and GP)	3000
Sand, silty sand, clayey sand, silty gravel and clayey gravel (SW, SP, SM, SC, GM and GC)	2000
Clay, sandy clay, silty clay, clayey silt, silt and sandy silt (CL, ML, MH and CH)	1500
Mud, organic silt, organic clays, peat or unprepared fill	0

Table 5.2: IBC 2011 Allowable Bearing Pressures (IBC, 2011).

Figure 5.1: Foundation Example for Container Buildings (Hermann, 2007).

Figure 5.2: Connection Examples for Container Buildings (Hermann, 2007).

	Tensile Strength	Tensile Strength (Lifting)	Compression Strength (Intermediate Plate)	Compression Strength (Cones)	Shear Strength
Twist Locks	150 kN (33.7 kip)	178 kN (40 kip)	850 kN (191 kip)	150 kN (33.7 kip)	300 kN (67.4 kip)
Latchlocks	150 kN (33.7 kip)	178 kN (40 kip)	850 kN (191 kip)	150 kN (33.7 kip)	300 kN (67.4 kip)
Stacking Fitting	0 kN (0 kip)	0 kN (0 kip)	850 kN (191 kip)	150 kN (33.7 kip)	300 kN (67.4 kip)

Table 5.3: Structural Limitations for Container Connection Devices (ISO 3874: Amd.1, 2000)

CHAPTER 6

SHIPPING CONTAINER COMPUTER MODELS

6.1 Overview

Chapter 6 discusses the computer modeling of a standard 20 ft ISO shipping container. The computer programs used to model the shipping containers and the computer modeling methodology are presented and discussed. Properties, mesh generation, considerations, comparisons, and model assumptions are presented for each shipping container computer model.

6.2 Computer Program Information

The shipping containers were modeled and analyzed using these programs: SolidWorks (2011), Hypermesh (2009), and Abaqus/CAE (2010). SolidWorks (2011) is a three-dimensional (3D) Computer Aided Design (CAD) program used to model 3D objects. Most components of a standard 20 ft ISO shipping container were modeled in SolidWorks (2011). Hypermesh (2009) is a program used to apply a finite element mesh to the components imported from SolidWorks (2011). Abaqus/CAE (2010) was the finite element analysis (FEA) program used to analyze the meshed container models imported from Hypermesh (2009).

SolidWorks (2011) was used to only create the geometries of 3D container components. Hypermesh (2009) was used to assign mesh, materials, and properties to the container components. Abaqus/CAE (2010) was used to modify the material and property assignments, apply loading and boundary conditions, define contact and connection properties, create the container simulation, and analyze the model. Abaqus/CAE (2010) also was used to create simplified container components and apply a mesh to these components.

The container simulations were either run on a laptop computer with 4GB of RAM or through the Ohio Super Computing Center (OSC). When OSC was used to analyze the complex container simulations, the job created in Abaqus/CAE (2010) was transferred to OSC. OSC ran the job simulation, and the files were saved onto the laptop for post processing. OSC used at least 16GB of RAM to run each simulation, and OSC would complete a given simulation at least ten times faster than the laptop computer.

6.3 General Shipping Container Model Information

Appendix C shows the fully modeled 20 ft ISO container with dimensions and assumptions for each component. The container model in Appendix C is very similar to an actual 20 ft ISO shipping container. The joining components of the container, e.g. corner fittings to corner posts, are almost fully welded to each other. The dimensions and container specifications presented in Appendix C came from multiple container manufacturers, but China International Marine Containers, Ltd. (CIMC) provided the most useful and complete set of documents for the container. The container model found

in Appendix C was too complex for this research's technology limitations, and the solution was to create simplified container models of the container model found in Appendix C.

Five computer models were created of a 20 ft ISO shipping container. Appendix E displays a step-by-step process for creating a component of the shipping container model using SolidWorks (2011), Hypermesh (2009), and Abaqus/CAE (2010). Simplified models of the actual 20 ft ISO shipping container were used to verify model assumptions, increase modeling efficiency, and show which components of the container could be simplified without sacrificing accuracy. The units used for the computer models in this research are: millimeter (mm), Newtons (N), tonne, seconds (sec), megapascals (MPa), and millijoule (mJ).

The material properties for each container component can be found in Table 6.1. All of the metal container components have a density of $7.85 \text{ E } 10^{-9} \text{ tonne/mm}^3$, Young's Modulus (E) equal to $200.0 \text{ E } 10^3 \text{ MPa (N/mm}^2\text{)}$, and Poisson's Ratio equal to 0.3. The yield stress (F_y) for each container component varies, but the majority of the container components have a F_y equal to 343.3 N/mm^2 (50 ksi).

The five container computer models vary in complexity and accuracy compared to the most detailed container model found in Appendix C. However, all five container models shared similar assumptions. The rear side of the container containing the doors, locking assembly, and hinges was replaced by an identical wall used for the front wall section or a non-corrugated wall section with similar properties. It was assumed that the rear door assembly could withstand the same loads as the front wall. All of the

connections were modeled to represent fully welded connections which could not fail.

The parts excluded from each container model are: flooring, hinges or hinge mechanisms, locking assembly hand bars, lashing fixtures, and most fillets.

In order to reduce computation time, simplified profiles of the container's components are used. The container models are labeled Model 1 through Model 5. The models increase in complexity, and Model 5 is most similar to the container model found in Appendix C (Figure C.1). Table D.1 displays each container component for the five shipping container models. The container component information found in Table D.1 displays each component's area (A), moment of inertia (I_{xx} and I_{yy}), dimensions, mesh density, and modeling assumptions. The X and Y axis (at the bottom left hand corner of each component snapshot) are for local coordinates per container component only, and the simplified cross section profiles are uniform over the entire length of the component (no holes, plates, or cut outs).

Each container component's cross section in Appendix C has a given area (A) and moment of inertia (I_{xx} and I_{yy}) value. Simplified cross sections are created with similar A , I_{xx} , and I_{yy} values as the container components found in Appendix C. Table 6.2 displays a comparison between a container component from Appendix C and a simplified version of it. It is impossible to match the simplified cross sectional properties with the original container components exactly, and the A , I_{xx} , and I_{yy} values have up to 1.0 % error tolerance between the Appendix C and simplified container components. Table 6.2 also presents the procedure to calculate the percentage error tolerance for the container components. Every component found on the simplified container is within the 1.0% error

tolerance except the walls and roof members. The walls and roof members are modeled using a rectangular solid shape for the simpler models. Eliminating the corrugation from the wall reduces the I_{xx} value significantly, I_{yy} is within a 5.0 % error, and A is within an approximate 25% error.

6.4 Container Model Creation and Meshing Procedures

The five simplified 20 ft ISO shipping container models were created using SolidWorks (2011) and Abaqus/CAE (2010). When each container model was created, different modeling methods were used simultaneously. A wire frame model was the simplest method to model the container. The process involved creating a series of 3D, deformable point features in Abaqus/CAE (2010) which were then connected by lines. The 2-node, linear line elements represented individual beam-column members of the container model. Each line of the wire frame was assigned a cross section profile, material property, and a mesh. Modeling line frame elements instead of a member with several thousand nodes and finite elements allowed faster computational times but decreased the accuracy of the model.

The wire frame elements were located at the centroid of the cross-section for each beam-column container member. The cross-sectional properties (i.e., A , I_{xx} , and I_{yy}) were used to calculate the stress, stiffness, and the overall displacement of the container. The container computer models appear to have overlapping container members when the component's profiles were shown in the models, but the wire frame model was unaffected.

The other method to model the shipping container's components was to create solid, 3D models of each component. The solid 3D models have a 3D solid tetramesh element pattern which filled the geometry of the component. The mesh of a solid 3D model created a meshed copy of component and was visible in the container models unlike the wire frame mesh. Although the computational time increased, the overall accuracy, response, and visual display of the model was increased. The solid 3D meshing option was applicable for beam or column like components of the container. For flat, thin sections without complicated cross sections, shell elements were used.

A 3D, deformable shell planar feature was created for the wall and roof sections of the container. A shell element allowed large, thin (flat or corrugated) sections of the container to be modeled quickly and accurately. Shell elements simplify a component by meshing a wire sheet (zero thickness) which mimics the geometry of the container component. The meshed sheet was then given a thickness corresponding to the container component's thickness, but when viewing the container model shell elements appear to have a zero thickness. Shell element sections are visually deceiving, but are more efficient than using solid, 3D elements for the walls and roof.

The meshing of the container components was done in Hypermesh (2009) and Abaqus/CAE (2010). Appendix E presents a guide showing the meshing procedure using Hypermesh (2009) and Abaqus/CAE (2010). In order to ensure the models were accurate, the elements of each container model were investigated for errors using an element quality check in Hypermesh (2009). Each element of the container model was checked to ensure it met certain finite element criteria, and the element quality check values for both

2D and 3D (tetrahedral) meshes are shown and described in Table 6.3. The element quality check values selected were based on commonly used values and engineering assumptions. The wire element type used was a B31 (2-node, linear line) element and the 3D solid element type was a C3D4 (Linear Tetrahedral) element. The shell element types were either S4R (linear quadrilateral, reduced integration), S4 (linear quadrilateral), or S3 (linear triangular) elements.

6.5 Shipping Container Model 1 and Model 2

Model 1 was the simplest shipping container model. All the container components were created and meshed (B31 wire beam and S4R shell elements) in Abaqus/CAE (2010). The shell mesh was uniform throughout the model, and the components' dimensional properties can be found in Table D.1. The overall dimensions of the wire box were 6058 mm x 2591 mm x 2438 mm, the yield stress was 343.3 N/mm^2 (50 ksi) for all the components, and the corner fittings were excluded from the model. Model 1 was constructed with 1,163 wire beam elements (B31) and 47,767 shell elements (S4R) for a total of 48,930 elements.

The wire container box members and shell walls were connected together using a tie constraint which kept the components connected regardless the container's displacement. The container connections selected were meant to simulate a weld which would not fail, and this allowed the container components to fail instead of connection failure. The actual ISO shipping container is fully welded at most connections, and failure at the welded joints is unlikely. The edges of the walls and roof are connected to

the beam wires, not to neighboring walls or roof edges. The four bottom corners of the container in Model 1 have a fully fixed boundary condition where the displacements and rotations are set equal to zero ($U1=U2=U3=UR1=UR2=UR3=0$).

Without corner fittings at the corners of the container, the container components in Model 1 interacted differently from the more complex container models. The container components at the corners were connected to each other instead of being connected to the face of the corner fitting. This made each component slightly longer than the actual container component. Figure 6.1 and Figure 6.2 display container Models 1 and 2 with a close up of the connection at the corner, and the wire beam profile overlap between components can be seen. Model 2 was exactly the same as Model 1, but had more accurate container component profiles (see Table D.1 for profile differences). Model 2 replaced many of the simplified container cross sections with the cross sections found in Appendix C.

6.6 Shipping Container Model 3

Model 3 had similar beam wire components as Model 2 with the addition of corner fittings and more detailed models for the walls and roof (Table D.1). The yield stress was 275 N/mm^2 (40 ksi) for corner fittings and 343.3 N/mm^2 (50 ksi) for everything else (as in Models 1 and 2). Unlike Models 1 and 2, the beam wire components were connected to the faces of the corner fittings. The walls and roof sections had square cut outs around the corner fittings.

The beam and column container components were created and meshed using B31 wire beam elements in Abaqus/CAE (2010). The corner fittings were created in SolidWorks (2011), uniformly meshed in Hypermesh (2009) with C3D4 linear tetrahedral elements, and then imported into Abaqus/CAE (2010). The walls and roof were created in SolidWorks (2011), meshed in Hypermesh (2009) using S3 linear triangular elements and S4 linear quadrilateral elements, and imported into Abaqus/CAE (2010). Model 3 was constructed with 1,063 wire beam elements (B31), 8,056 linear tetrahedral elements (C3D4), 45,845 shell elements (S4R or S4), and 292 shell elements (S3) for a total of 55,256 elements. The mesh density of the walls and roof increased around the corner cut outs to allow accurate stress distribution and to prevent abnormal stress concentration near the corners.

The centroid of the beam wire components are attached to the center point on each corner fitting's face which differs slightly from the actual container. The corner fittings are attached to the beam wire elements in Abaqus/CAE (2010) by a coupling constraint (kinematic, all degrees of freedom constrained). The coupling constraint tied the beam wire's end nodes to the elements of the corner fitting's face. The beam wire node connected to the face of the corner fitting was the coupling constraint control point, and most of the corner fitting's face was selected as the constraint region (the edges of the corner fitting's face were excluded). This constraint was an appropriate connection solution to attach a wire beam element to a solid section (B31 elements to C3D4 elements).

The beam wire elements and shell walls were connected together using a tie constraint similar to Models 1 and 2. The corner cut outs of each wall and roof were connected to the corner fittings using a shell-to-solid coupling. The edges of the wall and roof at the corner cut outs were selected as the shell edge surface, and the corner fitting face's interacting with the walls and roof were selected as the solid region surface (S4R elements to C3D4 elements). The four bottom corner faces of the container in Model 3 have a fully fixed boundary condition where the displacements and rotations are set equal to zero ($U1=U2=U3=UR1=UR2=UR3=0$). Figure 6.3 displays container Model 3 with connection and element details.

6.7 Shipping Container Model 4 and Model 5

Model 4 increased the container's complexity and was very comparable to the container model in Appendix C. Most of the components of the container were modeled as solid elements, similar to the corner fittings in Model 3. The cross members (flooring supporting members) were wire beam elements (similar to previous models) in order to reduce computation time. The walls and roof had corrugated profiles with uniform shell mesh configurations instead of flat walls used in previous models. The yield stress was 275 N/mm^2 (40 ksi) for corner fittings, 285 N/mm^2 (41 ksi) for inner rear corner posts, and 343.3 N/mm^2 (50 ksi) for all other components.

The cross members were created and meshed using B31 wire beam elements in Abaqus/CAE (2010). The corner fittings and container components were created in SolidWorks (2011), uniformly meshed in Hypermesh (2009) with C3D4 linear

tetrahedral elements, and then imported into Abaqus/CAE (2010). The walls and roof were created in SolidWorks (2011), meshed in Hypermesh (2009) using S3 linear triangular elements and S4 linear quadrilateral elements, and imported into Abaqus/CAE (2010). Model 4 was constructed with 78 wire beam elements (B31), 511,215 linear tetrahedral elements (C3D4), 64,077 shell elements (S4R or S4), and 668 shell elements (S3) for a total of 576,038 elements. Model 5 was constructed with 78 wire beam elements (B31), 511,215 linear tetrahedral elements (C3D4), 399,423 shell elements (S4R or S4), and 1,289 shell elements (S3) for a total of 912,005 elements.

The tie constraint was used to connect solid element components together. The faces of the connecting components were selected, and the slave surface was typically the component with the denser mesh. The cross members' wire elements were connected to the face of the base side rails using the coupling constraint. The cross member's wire end node was the coupling constraint control point, and a small section of the base side rail was selected as the constraint region. Most of the edges of the wall and roof were connected to the container components using a shell-to-solid coupling. The edge of the wall and roof touching the connecting container components were selected as the shell edge surface, and the component's surface interacting with the walls and roof was selected as the solid region surface (S4 and S3 elements to C3D4 elements).

The rear assembly of doors and locking assembly were replaced by a wall very similar to the front wall. However, the new rear wall's length was slightly longer and had a sloped bottom edge in order to connect into the door sill. Model 5 was exactly the same as Model 4 but with a denser mesh for the walls and roof (an increase of 335,967 shell

elements). The four bottom corners of the container in Models 4 and 5 have a fully fixed boundary condition where the displacements and rotations are set equal to zero ($U1=U2=U3=UR1=UR2=UR3=0$). Figure 6.4 displays container Models 4 and 5 with connection and element details.

6.8 Container Model Comparison Methodology

In order to verify the accuracy of the container models, a similar loading situation was applied to each container model, and the results were analyzed. Since every container model varied in complexity, the most accurate way to compare all the container models was to load each container until one component on the container began to yield.

Originally, the stiffness of each container model was to be compared. The stiffness of a structure or model is the slope of the linear relationship between the applied force and displacement in the elastic zone. The higher the slope value, the more resistive the container is to deformation. This methodology for comparing between the five models worked if the load acted on the component which yielded first. However, the container's components yielded at different locations throughout the container and not consistently at the loading location. With different container models of varying complexity, comparing the stiffness value for the whole container between models was inaccurate.

Instead of using the stiffness value to compare different container models, each container model was pushed under a displacement control at the front top corner fitting. The controlled displacement allowed the entire corner fitting to displace at constant

increments to a value in any direction. In this research, the top corner node or top corner fitting was displaced in the negative U3 direction by 150 mm (perpendicular to the sidewalls pushing inwards) and the top corner node displacement was monitored until a container component reached its yield stress (F_y).

Applying an external lateral loading onto the corner fitting was an option. However, if the force was increased at a constant rate, the force would suddenly stop if stiffness decreased or maximum strength was reached. By applying a displacement controlled loading, the displacement was increased at a constant rate. The force required to displace the container at each increment was calculated regardless of yielding or strength deterioration. This allowed the force to be accurately determined after yielding occurred in the container. Also, the controlled displacement allowed a better comparison between container models, because the corner fitting was forced to move only in the U3 direction.

A nonlinear analysis was performed in Abaqus/CAE (2010) until the corner fitting was displaced 150 mm. However, certain container components would reach their respective yield stresses (F_y) well before the 150 mm displacement was met. The history of the reaction force, displacement, and stress values throughout the container model were calculated and monitored during the analysis. The wire beam elements stress varied along the length of given element due to the beam's cross sectional profile. In these cases, the location of the largest stress on the wire beam element was used for comparison.

The stress analyzed in each simulation was from the element on the container which first yielded. Once the element reached its yield stress, the maximum reaction force at a corner node (Models 1 and 2) or node on the face of the corner fitting (Models 3, 4, and 5) was determined. This produced the force acting on the container when yielding began. The maximum displacement of the corner node or node on the face of the corner fitting was also determined when a container component first yielded. This methodology allowed accurate comparison between each container model.

Using the same methodology, a second simulation was performed using a linear analysis with an applied load on the corner node or face of the corner fitting. This linear analysis allowed for comparison of the stress, force, and displacement similar to the nonlinear analysis. However, multiple iterations were conducted on each model to determine the location of first yielding. When possible, the nonlinear analysis was preferred. The discussion of nonlinear and linear simulations is presented at the end of the chapter.

6.9 Container Model Comparison Results

The calculated results from five container models were compared in two simulations. The first simulation was a nonlinear analysis using displacement controlled lateral loading, and the container models were analyzed without walls or a roof. The second simulation was a linear analysis using an externally applied load, and the container models were analyzed with walls and roofs. For the first simulation, Figure 6.5 presents images of the container models before and after the analysis, Figure 6.6 displays

the amount of force and displacement required to reach first yielding in each container model. Table 6.4 displays each container model's maximum force, displacement, stiffness, and yield location when a container component first yielded. Figure 6.6 shows a linear response because the force and displacement values after yielding were not plotted.

As the complexity of models increase (Model 5 most complex), the rigidity or stiffness of the model increases and the displacement decreases. At yielding, the laterally displaced nodes at the top corner of Model 1 move 28 mm (1.18 in.) more than Model 5. The force required to reach yielding in the container decreased between Models 1 and 2 as more accurate container components replaced the simplified box cross section components (from 33,093 N to 29,337 N). The force required to reach yielding for Models 4 and 5 was between the values for Model 2 and Model 3. The first yielding typically occurred at the front corner post (attached to displaced top corner fitting) near the top and bottom corner fittings. Figure 6.7 displays the stress distribution at yielding for each container model.

For the second simulation, Figure 6.8 presents images of the container models before and after the analysis, Figure 6.9 displays the amount of force and displacement required to reach first yielding in each container model. Table 6.5 displays each container model's maximum force, displacement, stiffness, and yield location when a container component first yielded.

The first yielding occurred at the front wall and roof at the corner with the applied load for Model 1, the front wall near the bottom corner fitting (diagonal from loading) for Models 2 and 3, and the front corner post (attached to corner with loading) near the

bottom corner fitting for Models 4 and 5. Figure 6.10 displays the stress distribution at yielding for each container model. All of the models have a comparable response except Model 3. Model 3 had unique corner cut outs in the walls and roof which generated stresses not comparable to the shipping container in Appendix C or other models. Figure 6.11 displays Model 3 with a close up of the stress near the corner cut outs.

The displacement for the other models was within 1 mm (0.04 in.) of each other, and the applied forces at yielding ranged from 253 kN to 319 kN (56.9 kip to 71.7 kip). The simulation time to run Model 5 was approximately 2 hours, Model 4 was 30 minutes, and Models 1 and 2 were 15 minutes. Although the simulation time for Model 5 was four times greater than Model 4, both models produced almost identical results.

The differences in displacements calculated from the container models were mostly due to a couple of factors. The container members in Appendix C contain cut outs, fillets, and other modifications. The container members in Models 1, 2, and 3 did not have many of these modifications. The simplified container components (Table 6.2 and Table D.1) had similar cross sectional properties as the components found on the container in Appendix C (Figure C.1), but the simplified hollow box cross sections may have affected the container's stiffness and displacement at yielding point. Table 6.4 shows that Model 1 (simplified box section components) could withstand a larger applied force than Model 2 with more accurate and complex container components.

Container models of varying complexity were compared under similar loading conditions. The intent of this research was to use a container model most similar to the complex container model in Appendix C, because the connections and reactions between

container components could not be properly captured in simpler models (Models 1, 2, and 3). Model 4 was chosen as the most efficient model. Model 4 had connections representing the actual container, yet simple enough to produce acceptably accurate stiffness, strength, and deformations. It had a comparable response with Models 1 and 2 and contained very similar connections and container components as the container model in Appendix C.

6.10 Discussion of Analysis and Modeling Assumptions

The container models each presented unique issues which led to different analysis approaches. Although it required a longer simulation time, performing a nonlinear analysis was the most efficient method for analyzing the container models. The nonlinear analysis allowed the container model to yield and reach plastic response under very small displacement increments. Also, only one simulation was required per model to produce the results presented in Chapter 6 (Figures 6.5, 6.6, and 6.7 and Table 6.4). However, once the container's walls and roof were added to the models (second simulation), the nonlinear simulations did not converge and exited with an error partially through the analysis. After many tests and theories, the error in nonlinear analysis could not be fixed.

In place of the nonlinear analysis, a linear analysis was performed for the remainder of the research (Figures 6.8, 6.9, and 6.10 and Table 6.5). A linear analysis simulation generated values in the elastic range and the analysis was stopped once the first yield stress was reached in any element. A linear analysis produced similar results to the nonlinear analysis, but the linear simulations required multiple iterations in order to

determine the exact applied loading value which first caused yielding in a container component.

Another issue during the simulations was the selection of node location on the corner fitting's face for applying the controlled displacement. Originally, a single node was selected to be displaced 150 mm on the corner fitting's face. However, this created a different loading scenario which could not easily be compared to Models 1 or 2 (do not contain corner fittings). Also, as the models complexity increased, a single node under constant displacement increments on the corner fitting would create abnormal stresses on the corner fitting as shown in Figure 6.12.

Instead of a single node selection, the entire outer face of the corner fitting was displaced under constant displacement increments. This worked well for the simpler container models, but as the models increased in complexity, the outer face of the corner fitting yielded before any of the container's components did. Figure 6.13 displays a corner fitting yielding on its edges. The possibility of pushing a rigid plate onto the outer face of the corner fitting was an option, however it would have created numerous new loading scenarios and contact surface modeling.

The final solution used in this chapter was increasing the yield stress of the corner fittings to 1000 N/mm^2 (275 N/mm^2 was the normal yield stress) to ensure the corner fitting subjected to the external load would not reach yielding before another component of the container did. Although this procedure was not completely accurate in reality, it produced a similar comparison between all five models. This procedure produced

container model deformations which appear to not fail (Figure 6.8) due to the high yield stress of the corner fitting but produced accurate results.

Material (JIS Designation)	Description	ASTM Designation	Yield Stress (F_y)	Tensile Stress (F_u)	Location on ISO Container
Corten A or COR-TEN A	Weathering Steel, Corrosion Resistant, High-Strength, Low-Alloy	A242	50 ksi (35 kg/mm ²)	70 ksi (49 kg/mm ²)	<i>Front End Assembly:</i> Front Corner Post, Front Sill, Front Wall, Front Header <i>Base Assembly:</i> Bottom Side Rail, Crossmember, Fork Pocket Assembly, Floor Center Rail <i>Rear End Assembly:</i> Rear Corner Post (outer), Rear Header Cap, Door Header, Door Sill, Door Panel Frame, Door Panel <i>Side Wall Assembly:</i> Side Wall, Top Side Rail <i>Roof:</i> Roof Corner Gusset, Roof Panel
SCW49 or SCW480	Casted Weldable Steel	A216	40 ksi (28 kg/mm ²)	70 ksi (49 kg/mm ²)	Corner Fitting
S20C	Forged Weldable Steel	A53 Gr. B	35 ksi (25 kg/mm ²)	60 ksi (42 kg/mm ²)	Locking Cam, Locking Cam Keeper
S25C	Threaded Standard Fasteners	A307	40 ksi (28 kg/mm ²)	65 ksi (46 kg/mm ²)	Door Hinge
<u>NOT USED:</u> SM490A or SM50A	Hot Rolled, Hi-Tensile Steel	?	47 ksi (33 kg/mm ²)	71 ksi (50 kg/mm ²)	Rear Corner Post (Inner), Front Corner Posts, Door Sill, Front Bottom End Rail
<u>NOT USED:</u> SM50YA	Hot Rolled, Hi-Tensile Steel	?	53 ksi (37 kg/mm ²)	71 ksi (50 kg/mm ²)	Rear Corner Post (Inner)
SS50	Hot Rolled, Hi-Tensile Steel	A1011 or A414	41 ksi (29 kg/mm ²)	71 ksi (50 kg/mm ²)	Rear Corner Post (Inner)
SS41	Hot Rolled, Shaped Steel	A283	35 ksi (25 kg/mm ²)	58 ksi (41 kg/mm ²)	Lashing Bar & Lashing Ring on Side Wall
STK41	Structural Steel Round Pipe (Carbon)	A501	36 ksi (25 kg/mm ²)	58 ksi (41 kg/mm ²)	Door Locking Bars/Rods
SUS304	Stainless Steel	A276-304	?	>53 ksi	Door Gasket Retainer, Door Hinge Pins, Washer, Rivet
Floor Board	19 Ply (28 mm thick), Apitong or Keruing or Hardwood Plywood	NA	?	?	Flooring

Table 6.1: Shipping Container Material Information.

Door Sill Cross Section from Appendix C	Simplified Door Sill Cross Section
<p>Cross Section Properties:</p> <p>Dimensions: Figure C.10 (Appendix C)</p> <p>$A = 2.74 \text{ in}^2 (1770 \text{ mm}^2)$</p> <p>$I_{xx} = 19.46 \text{ in}^4 (8.0\text{E}6 \text{ mm}^4)$</p> <p>$I_{yy} = 6.11 \text{ in}^4 (2.5\text{E}6 \text{ mm}^4)$</p>	<p>Cross Section Properties:</p> <p>186 x 89 x 3.3 mm</p> <p>$A = 2.75 \text{ in}^2 (1771 \text{ mm}^2)$</p> <p>$I_{xx} = 19.41 \text{ in}^4 (8.0\text{E}6 \text{ mm}^4)$</p> <p>$I_{yy} = 6.16 \text{ in}^4 (2.5\text{E}6 \text{ mm}^4)$</p>
Percentage Error Comparison	
<p>Comparing the A Value: $\frac{2.75 \text{ in}^2 - 2.74 \text{ in}^2}{2.74 \text{ in}^2} = 0.36 \% \text{ error} < 1.0\%$</p> <p>Comparing the I_{xx} Value: $\frac{19.41 \text{ in}^4 - 19.46 \text{ in}^4}{19.46 \text{ in}^4} = 0.25 \% \text{ error} < 1.0\%$</p> <p>Comparing the I_{yy} Value: $\frac{6.16 \text{ in}^4 - 6.11 \text{ in}^4}{6.11 \text{ in}^4} = 0.81 \% \text{ error} < 1.0\%$</p>	

Table 6.2: Appendix C (Figure C.10) and Simplified Container Component Cross Section Comparison.

☐ 1-d ☒ 2-d ☐ 3-d ☐ time ☐ user ☐ group	warpage	>	5 . 0 0 0	length	<	0 . 0 0 0	connectivity
	aspect	>	5 . 0 0 0	jacobian	<	0 . 7 0 0	duplicates
	skew	>	6 0 . 0 0 0	taper	>	0 . 5 0 0	settings...
	chord dev	>	1 . 0 0 0				save failed
	quads:			trias:			assign plot
	min angle	<	4 5 . 0 0 0	min angle	<	1 0 . 0 0 0	visual options
	max angle	>	1 3 5 . 0 0 0	max angle	>	1 6 0 . 0 0 0	return
☐ 1-d ☐ 2-d ☒ 3-d ☐ time ☐ user ☐ group	warpage	>	5 . 0 0 0	length	<	0 . 0 0 0	connectivity
	aspect	>	5 . 0 0 0	jacobian	<	0 . 7 0 0	duplicates
	skew	>	6 0 . 0 0 0	vol skew	>	0 . 7 0 0	settings...
	tet collapse	<	0 . 3 0 0	vol AR	>	5 . 0 0 0	save failed
	quad faces:			tria faces:			assign plot
	min angle	<	4 5 . 0 0 0	min angle	<	1 0 . 0 0 0	visual options
	max angle	>	1 3 5 . 0 0 0	max angle	>	1 6 0 . 0 0 0	return
Warpage - Maximum angle between the two planes of triangles created by splitting a quad element diagonally, range 0- 90 (worst)							
Aspect - Ratio of longest side to the shortest side of an element.							
Skew - The minimum angle between two lines joining opposite mid-sides of the element (Quads), the minimum angle between the vector from each node to the opposing mid-side and the vector between the two adjacent mid-sides at each node of the element (Trias), range 0- 90 (worst)							
Chord Dev - The farthest distance between the middle of an edge to its project on the corresponding surface or inferred surface							
Length – Varied per model							
Jacobian - Measure of the deviation of a given element from an ideally shaped element, the check is performed by mapping an ideal element in parametric coordinates onto the actual element, range 1 to -1 (worst)							
Taper - As the taper approaches 0, the shape approaches a rectangle							
Tet Collapse - As the tetra collapses, the value approaches 0.0, while a perfect tetra has a value of 1.0							
Vol Skew - Defined as 1-shape factor, so a skew of 0 is perfect and a skew of 1 is the worst possible value							
Vol AR - The length of the longest edge divided by the length of the shortest altitude.							
Quad Min Angle - Minimum internal angle of a quad element, range 90-0 (worst)							
Quad Max Angle - Maximum internal angle of a quad element, range 90- 180 (worst)							
Trias Min Angle - Minimum internal angle of a triangle element, range 60- 0 (worst)							
Trias Max Angle - Maximum internal angle of a triangle element, range 60- 180 (worst)							

Table 6.3: Hypermesh (2009) Element Quality Check Information.

Figure 6.1: Container Model 1.

Figure 6.2: Container Model 2.

Figure 6.3: Container Model 3.

Figure 6.4: Container Model 4 and Model 5.

Model 1	Model 2	Model 3	Models 4 & 5
Beam Profiles Rendered	Beam Profiles Rendered	Beam Profiles Rendered with Corner Fittings	Beam Profiles Rendered with Solid Components

Model 1	Model 2	Model 3	Models 4 & 5
Container at First Yielding	Container at First Yielding	Container at First Yielding	Container at First Yielding

Figure 6.5: Shipping Container Models (No Walls or Roof) Before and After First Yielding Occurs.

Figure 6.6: Calculated Force Displacement Relationship for each Model up to Yielding (No Walls or Roof on Container).

	Displacement	Force	Stiffness	First Location to Reach Yielding
Model 1	46.9 mm (1.85 in.)	33093 N (7.43 kip)	706 N/mm (4.0 kip/in.)	Front Header at Corner Fittings
Model 2	30 mm (1.18 in.)	29337 N (6.6 kip)	978 N/mm (5.6 kip/in.)	Front Corner Post near bottom Corner Fittings
Model 3	29 mm (1.14 in.)	46935N (10.6 kip)	1618 N/mm (9.2 kip/in.)	Front Corner Post near top & bottom Corner Fittings
Model 4 & 5	18.75 mm (0.74 in.)	39750 N (8.9 kip)	2120 N/mm (12.1 kip/in.)	Front Corner Post near top Corner Fitting

Table 6.4: Maximum Force, Displacement, and Stiffness for each Model (No Walls or Roof) at Yielding.

Figure 6.7: Stress Distribution at Yielding for each Model in Simulation 1 (Nonlinear).

Model 1	Model 2	Model 3	Model 4	Model 5
Beam Profiles Rendered	Beam Profiles Rendered	Beam Profiles Rendered with Corner Fittings	Beam Profiles Rendered with Solid Components	Beam Profiles Rendered with Solid Components

Model 1	Model 2	Model 3	Model 4	Model 5
Container at First Yielding	Container at First Yielding	Container at First Yielding	Container at First Yielding	Container at First Yielding

Figure 6.8: Shipping Container Models Before and After First Yielding Occurs.

Figure 6.9: Calculated Force Displacement Relationship for each Model up to Yielding.

	Displacement	Force	Stiffness	First Location to Reach Yielding
Model 1	3.92 mm (0.15 in.)	299 kN (67.2 kip)	77 kN/mm (439 kip/in.)	Front Wall & Roof at Corner with loading
Model 2	3.80 mm (0.149 in.)	319 kN (71.7 kip)	84 kN/mm (480 kip/in.)	Front Wall at bottom corner fitting (diagonal from loading)
Model 3	1.80 mm (0.07 in.)	50 kN (11.2 kip)	28 kN/mm (160 kip/in.)	Front Wall at bottom corner fitting (diagonal from loading)
Model 4	3.18 mm (0.125 in.)	253 kN (56.9 kip)	80 kN/mm (457 kip/in.)	Front Corner Post at bottom corner fitting (near front sill)
Model 5	3.18 mm (0.125 in.)	253 kN (56.9 kip)	80 kN/mm (457 kip/in.)	Front Corner Post at bottom corner fitting (near front sill)

Table 6.5: Maximum Force, Displacement, and Stiffness for each Model at Yielding.

Figure 6.10: Stress Distribution at Yielding for each Model in Simulation 2 (Linear).

Figure 6.11: Model 3 Unrealistic Stresses (Compared to Appendix C Container).

Figure 6.12: Single Point Controlled Displacement with Abnormal Results.

Figure 6.13: Yielding in Corner Fitting from Controlled Displacement.

CHAPTER 7

MODIFIED SHIPPING CONTAINER SIMULATIONS

7.1 Overview

Based on comparisons of response from five models in Chapter 6, Model 4 was selected as the optimum container model in terms of model complexity and accuracy. Model 4 was modified slightly in the remainder of the research. Chapter 7 presents a series of loading scenarios acting on the unmodified container model, and the container is then modified and applied the same loading scenarios. Yielding locations, displacements, stresses, forces, and container behavior are discussed and analyzed for each loading scenario and modification.

7.2 Loading Scenarios for Shipping Container Model

Yielding of shipping container models were investigated under different loading scenarios. Therefore, the safety factors, design loads, and structural code considerations required to keep structures from yielding were not considered. The only relevant structural information for the container models came from the structural tests presented in ISO 1496-1 (discussed in Chapter 3). Table A.7 in Appendix A presents the applied loads a 20 ft ISO shipping container should be able to withstand. Using these specified loading

values from ISO 1496-1 as a reference, five loading scenarios were applied to the container models and analyzed.

The loading scenarios can be found in Figure 7.1. Each loading scenario was applied to the container model until one of the container members yielded. The analysis followed the linear simulation methodology presented in Chapter 6 using incrementally increasing externally applied load instead of displacement controlled simulations. The point loads applied to each corner fitting are uniform surface loads in Abaqus/CAE (2010). When multiplied by the area of the specific corner fitting face, the uniform loading equaled the same force value used to compare the response of container models.

Loading scenario 1 (Figure 7.1) simulated a stacking load by applying a point load on the top face of each of the four corner fittings attached to the roof. Loading scenario 2 simulated stacking on the shorter side of the container by applying a point load on the two top surfaces of corner fittings attached to the roof (in plane with front or rear wall). Loading scenario 3 simulated stacking on the longer side of the container by applying a point load on two top surfaces of corner fittings attached to the roof (in plane with sidewalls). Loading scenario 4 applied two transverse point loads (acting on the longer side of the container) to the side surfaces of two corner fittings attached to the roof (acting inwards). Similar to loading scenario 4, loading scenario 5 applied two longitudinal point loads (acting on the shorter side of the container).

7.3 Final Shipping Container Model

Model 4 developed in Chapter 6 had to be slightly modified. The original container Model 4 from Chapter 6 produced unrealistic stress concentrations in various areas of the container during compression loading scenarios described above. The stress build ups were caused by missing plate reinforcing, not modeling the large weld beads found on real containers, or using too coarse of mesh. After further investigating the container manufacturer plans and reviewing an actual container, additional reinforcing was added to the container and mesh density was increased. Figure 7.2 displays the additional plate reinforcing on certain container members produced by certain manufacturers.

Most of the calculated abnormal stresses disappeared after the addition of plates and increased mesh density. Figure 7.3 displays multiple examples of abnormal stress build ups on the container model before and after the addition of reinforcing plates and increased mesh density. Table D.2 displays the final container model's element quality checks from Hypermesh (2009), meshing information, and Abaqus/CAE (2010) simulation warnings regarding the mesh. The final container model was constructed with 5,256 wire beam elements (B31), 3,174,025 linear tetrahedral elements (C3D4), 232,914 shell elements (S4R or S4), and 1,269 shell elements (S3) for a total of 3,413,464 elements. The connections in the final container model were the same as Model 4 in Chapter 6.

7.4 Shipping Container Model Modifications

The base container model was modified and analyzed to investigate the contribution of different components to total response of the container. Each container model was modified by removing full wall sections or the entire roof instead of cutting out holes for windows or doors. This was believed to provide a more conservative approach to using the modified shipping containers. Figure 7.4 displays the original container model (revised Model 4) and seven modified 20 ft ISO shipping container models. The original unmodified container is labeled M1. The container labeled M2 has the sidewalls removed, M3 has the end walls removed, M4 has the roof removed, M5 has the sidewalls and endwalls removed, M6 has one sidewall removed, M7 has the rear endwall (doors) removed, and M8 has all of the walls and roof removed. The connections and mesh density for each modified model are the same as the original container model, but the modified container components have their connections removed from the models as well. The modified container models were subjected to the five loading scenarios shown in Figure 7.1.

7.5 Abaqus/CAE (2010) Model Simulation Warnings

Every container computer simulation ran in Abaqus/CAE (2010) generated simulation and element quality check warnings. The Abaqus/CAE (2010) simulation warnings generally were related to connection issues in each model and were seen as insignificant. Table 7.1 discusses each of the simulation warnings generated in Abaqus/CAE (2010). The element quality check warnings generated in Abaqus/CAE

(2010) were from poor meshing in Hypermesh (2009). Table D.2 displays element quality check warnings generated in Abaqus/CAE (2010) for each container member.

The elements which did not pass the element quality check in Abaqus/CAE (2010) generally failed by a very small, insignificant amount. Also, the elements in question were not located near any connections or high stress concentrations. Distorted tetrahedral elements found on the door header, door sill, and front header failed the Abaqus/CAE (2010) quality check within a couple of degrees. The distorted isoparametric elements on the roof generally failed the quality check by ten degrees, and the warped elements on the roof were seen as insignificant.

7.6 Loading Scenario 1 Results

The goal of Loading Scenario 1 (Figure 7.1) was to determine how much weight could be stacked on top of an unmodified and modified container. Figure 7.5 displays a graph comparing of the maximum applied force, displacement, and stiffness values at yielding for each container model. Table D.3 presents the eight container models' responses to Loading Scenario 1. The magnitude of the applied force, displacement, and stiffness at first yielding of a container component in each model are displayed. The stresses, yielding locations, and container model reactions are also presented. The final part of Table D.3 presents similarities between the response of different container models during Loading Scenario 1.

All of the models subjected to Loading Scenario 1 first yielded at the door header component. The complete container (model M1) and container modifications removing

just sidewalls or the roof (models M2, M4, and M6) yielded under tension at the underside of the door header near the corner fitting's edge touching the door header. The modified models without an endwall or both endwalls (models M3, M5, M7, and M8) yielded where the door header connected into the rear corner post under compression.

The container models containing endwalls (models M1, M2, M4, and M6) had similar maximum applied force values. However, there was an 84% reduction in stiffness from M1 when the sidewalls were removed (model M2). The container models with one or both endwalls removed (models M3, M5, M7, and M8) had an average 23% reduction in maximum applied force and a reduction in stiffness ranging from 87% to 90% when compared to M1. All of the container models had a shorter simulation time than M1.

For Loading Scenario 1, the removal of sidewalls or the roof did not have an effect on the maximum applied loading values. For the unmodified container model (M1), the calculated yield axial load of 942 kN was very close to the 942 kN specified in ISO 1496-1 (Table A.7). The endwalls under Loading Scenario 1 were the most critical load resisting components, and were more effective at carrying the loads than the sidewalls. The single endwall removed model (model M7) had a greater reduction in maximum applied force and stiffness than the model with both sidewalls removed (model M2) when both were compared to the base model M1.

7.7 Loading Scenario 2 Results

The goal of Loading Scenario 2 (Figure 7.1) was to determine how much weight could be stacked on top of an unmodified and modified container (on the container's

shorter side). Figure 7.6 displays a graph comparing of the maximum applied force, displacement, and stiffness values at yielding for each container model. Table D.4 presents the eight container models' responses to Loading Scenario 2. The magnitude of the applied force, displacement, and stiffness at first yielding of a container component in each model are displayed. The stresses, yielding locations, and container model reactions are also presented. The final part of Table D.4 presents similarities between the response of different container models during Loading Scenario 2.

All of the models except M7 first yielded at the front corner post where it was attached to the top corner fittings, because the loading was applied over the front top corners. The modified model without an endwall (model M7) yielded where the door header connected into the rear corner post under compression, because the loading was applied over the rear top corners.

M7 had significantly different values from the other container models. M7 had a 31% maximum applied force and 88% stiffness reduction compared to the base model M1. The modified models with various walls removed (models M2, M3, M5, M6, and M8) had an average 10% increase in maximum applied force and a reduced stiffness up to 71% compared to M1. Also, every model had a shorter simulation time compared to model M1. The less stiff models were able to withstand slightly larger applied forces, because they deflected significantly more than the base container model M1 allowing the loading to distribute more throughout the container.

The sidewalls under Loading Scenario 2 were the most critical load resisting components, and the endwalls were somewhat effective at carrying the loads. The

calculated yield load was 942 kN for the full model (M1) was comparable to an assumed 942 kN specified in ISO 1496-1 (Table A.7). The modified models with both sidewalls removed (models M2, M5, and M8) had an average 10% increase in maximum applied load and a 70% reduction in stiffness when compared to the complete container model M1. However, the model with both endwalls removed (model M3) had an 11% increase in maximum applied force, but only had a 44% reduction in stiffness when compared to M1. The addition or removal of the roof did not provide much stiffness or strength in Loading Scenario 2. The results for the model with one endwall removed (Model 7) were not comparable to the other container models, because the two vertical loads were applied over the rear side of the container.

7.8 Loading Scenario 3 Results

The goal of Loading Scenario 3 (Figure 7.1) was to determine how much weight could be stacked on top of an unmodified and modified container (on the container's long side). Figure 7.7 displays a graph comparing of the maximum applied force, displacement, and stiffness values at yielding for each container model. Table D.5 presents the eight container models' responses to Loading Scenario 3. The magnitude of the applied force, displacement, and stiffness at first yielding of a container component in each model are displayed. The stresses, yielding locations, and container model reactions are also presented. The final part of Table D.5 presents similarities between the response of different container models during Loading Scenario 3.

Models without endwalls (models M3, M5, M7, and M8) first yielded where the door header connected into the rear corner post under compression. The models containing endwalls (models M1, M2, M4, and M6) yielded under tension at the underside of the door header near the corner fitting's edge touching the door header.

Every model except M4 (no roof) had larger maximum applied force value, but the stiffness values were reduced up to 86% compared to the base container model M1. The models containing roofs without both endwalls (models M3 and M5) had simulation times 200 seconds longer than M1. The roof appeared to only affect the container model without any walls (model M5) by increasing the maximum applied loading and stiffness values slightly from the container model without any walls or roof (model M8).

Loading Scenario 3 resulted in a distinctive response pattern. As more components were removed from the container (beginning with the sidewalls) the maximum applied force value increased, and the models became more flexible, which in turn, delayed yielding. The endwalls under Loading Scenario 3 were the most critical load resisting components. The sidewalls also carried significant load and provided stiffness, especially in the absence of the endwalls. The less stiff models were able to withstand larger applied forces, had larger displacements, and yielded in similar locations compared to the unmodified container model M1.

7.9 Loading Scenario 4 Results

The goal of Loading Scenario 4 (Figure 7.1) was to determine how much lateral force could be applied to the long side of an unmodified and modified container. Figure

7.8 displays a graph comparing of the maximum applied force, displacement, and stiffness values at yielding for each container model. Table D.6 presents the eight container models' responses to Loading Scenario 4. The magnitude of the applied force, displacement, and stiffness at first yielding of a container component in each model are displayed. The stresses, yielding locations, and container model reactions are also presented. The final part of Table D.6 presents similarities between the response of different container models during Loading Scenario 4.

The container models with endwalls (models M1, M2, M4, and M6) first yielded in tension where the door header protection plate connects to the top corner fitting closest the applied load. The model with one endwall (model M7) yielded in tension near the edge of the roof where it connects to the side rail approximately 1.8 meters (6 ft) away from the rear side (door end) of the shipping container. The container models without both endwalls (models M3, M5, and M8) yielded at the front corner post where it connects to the front header (opposite side of the applied loading).

The base container model M1 had the largest maximum applied force, largest stiffness, and the longest simulation time compared to the other modified container models. The largest reduction in maximum applied force for a container model with and without endwalls was 10% and 97% respectively (models M6 and M3) when compared to M1. The maximum reduction in stiffness for a container model with and without endwalls was 6% and 99.5% respectively (models M4 and M5) when compared to M1.

Container models with endwalls (models M1, M2, M4, M6, and M7) had higher maximum applied forces and were significantly stiffer than container models without

endwalls (M3, M5, and M8). The endwalls under Loading Scenario 4 were the critical lateral load resisting components. The lateral capacity of the sidewalls and roof components was very limited, and the roof component provided little resistance without wall components (models M5 and M8). Only the complete model (M1) reached the maximum elastic load of 150 kN listed in ISO 1496-1 (Table A.7).

7.10 Loading Scenario 5 Results

The goal of Loading Scenario 5 (Figure 7.1) was to determine how much lateral force could be applied to the short side of an unmodified and modified container. Figure 7.9 displays a graph comparing of the maximum applied force, displacement, and stiffness values at yielding for each container model. Table D.7 presents the eight container models' responses to Loading Scenario 5. The magnitude of the applied force, displacement, and stiffness at first yielding of a container component in each model are displayed. The stresses, yielding locations, and container model reactions are also presented. The final part of Table D.7 presents similarities between the response of different container models during Loading Scenario 5.

The container model without a roof (model M4) first yielded in tension at the corner of the front header connected to the top siderail. The container models M1, M3, and M6 all yielded at the roof in compression near the applied loading. The container model with one endwall (model M7) yielded at the door header in compression where it connects to the roof and top side rail. The container models without sidewalls (mode M2,

M5, and M8) all yielded at the front corner post in compression where it connected into the base side rails.

Container models with both sidewalls removed (M2, M5, and M8) had significantly smaller maximum applied force and stiffness values compared to the base container model M1. The models without both sidewalls had an average 81% reduction in maximum applied force and a 98% reduction in stiffness compared to M1. The original container model M1 had comparable maximum applied force and stiffness values to the container model with both endwalls removed (model M3). However, the container model with one endwall (model M7) had a 35% maximum applied force reduction, an 18% stiffness reduction, and a simulation time increase of 1361 seconds when compared to M1. The loading for M7 was applied on the door side of the container whereas the loading for M3 was applied at the front of the container model.

The sidewalls under Loading Scenario 5 were the critical lateral load resisting components. The complete model (M1) reached the maximum elastic load of 75 kN listed in Table A.7, which was well below the maximum load (124.5 kN) resisted by the model without a roof (M4). Models containing both sidewalls and the roof (models M1 and M3) were the most rigid. The container model without a roof (model M4) had a 66% maximum applied force increase and a 26% reduction in stiffness when compared to M1. The container reached yielding in the roof component near the front header in the original model M1, but without the roof (model M4) the container yielded at the front header. The change of yielding location may have caused the increase in maximum applied loading for M4 (roof removed) when compared to the original container model M1.

7.11 Overview of Results

All of the container models yielded at the door header component when subjected to Loading Scenario 1. The endwalls under Loading Scenario 1 are the most critical load resisting components, and were more effective at carrying the loads than the sidewalls.

For Loading Scenario 2, all of the models except M7 first yielded at the front corner post where it was attached to the top corner fittings. The sidewalls under Loading Scenario 2 are the most critical load resisting components, and the endwalls were somewhat effective at carrying the loads.

All of the container models yielded at the door header component when subjected to Loading Scenario 3. The endwalls under Loading Scenario 3 are the most critical load resisting components. The sidewalls were also carrying significant load, especially in the absence of endwalls. The less stiff models were able to withstand larger applied forces, had larger displacements, and yielded in similar locations compared to the unmodified container model M1.

The roof did not have any significant structural contribution when subjected to vertical point loads (Loading Scenarios 1, 2, and 3). When subjected to the vertical point loads from Loading Scenarios 2 and 3, the original container model M1 had lower maximum applied forces compared to the other container models. When all four walls were present in the container model (M1 and M4), a localized yield stress in the door header may have occurred resulting in a reduced maximum applied force compared to the other container models.

The endwalls under Loading Scenario 4 were the critical lateral load resisting components. The lateral capacity of the sidewalls and roof components are very limited, and the roof component provided little resistance without wall components (models M5 and M8).

The sidewalls under Loading Scenario 5 were the critical lateral load resisting components. Models containing both sidewalls and the roof (models M1 and M3) were the most rigid, and the container model without a roof (model M4) had a 66% maximum applied force increase and a 26% reduction in stiffness when compared to M1. The yield location changed when the roof was removed (M4) which may have caused the increase in maximum applied force for M4 (roof removed) when compared to the original container model M1.

7.12 Factors Affecting Model Simulations

The unmodified container model (M1) used for the simulations (Table D.2) reached yielding at different applied loads than what ISO 1496-1 (Table A.7) required for each loading scenario. The calculated and expected values differed as much as three times for some loading scenarios. The end of Chapter 7 describes how the calculated and expected container values were adjusted. The container models generally were able to withstand a larger transverse load and a smaller compressive load than what ISO 1496-1 (1990) recommended. The difference in values could be caused by a number of factors.

The mesh density and meshing methodology may not have been completely accurate or sufficient for some members of the container models. The accuracy of the

analyses may have been improved by increasing the density of the mesh around high concentrated stress areas, using a different mesh pattern for 3D solids, or by incorporating different mesh strategies for the walls and roof.

There are several possibilities to model the same container component. There are many different cross section profiles for each component of the shipping container. Appendix C presents the different cross section modeling options for each component of the shipping container. ISO certified containers incorporate any number of these cross section profiles into a given container, and it is unknown how many are used interchangeably. This creates same size shipping containers using different components with varying structural strengths. The combination of cross sections chosen in the research may have been an incorrect combination of container components, but this is difficult to verify. It is also difficult to verify the component details for the containers referenced in ISO 1496-1 (1990).

The shipping container manufacturing plans were very difficult to find. There were multiple Chinese shipping container manufacturing plans used for this research, but only one complete set of plans was available. Different manufacturers and container companies used different values for yield strengths, reinforcing, and components. Also, some of the newer container documents created by the manufacturing companies did not meet structural requirements of the latest ISO 1496-1 amendments. The container manufacturing plans usually contained unclear details for reinforcing and plates for the containers. The reinforcing and plates have the potential to significantly increase the container's ability to withstand different loading scenarios. However without more

accurate or consistent container documents, the reinforcement and plates were only as accurate as the plans available. A visual inspection of an actual container did not help to determine some component details. Much of the reinforcement and plates were hidden or concealed behind other container components.

Aside from different manufacturing plans, some of the container components were modeled slightly differently and were simplified due to ease of modeling. Appendix C presents the assumptions and modeling differences. One simplification which may have affected the container's structural integrity was the usage of 1.6 mm width for the sidewalls, instead of using 2.0 mm wide sidewalls near the corner posts. Modeling shell elements for the sidewalls was difficult when the thickness varied from 1.6 to 2.0 mm. Many of the connections between container components were fully welded, and the weld beads are at least a ½ inch in diameter and usually larger. The weld beads fill the connections between the container components and create additional reinforcing which was not modeled on the computer simulations.

Along with the weld beads, certain fillets were excluded from the modeling process. The dimensions for most of the fillets were not given in the manufacturing plans. Certain fillets decreased the stress build up in certain container connections significantly, e.g., the front corner post to the corner fittings, and the exclusion of certain fillets may have led to yielding of certain container components unrealistically. This was difficult to verify, and most of the yielding points on the container were not located at fillet points.

7.13 Accounting for Container Computer Model Differences from ISO 1496-1

The ISO shipping container's structural strengths presented in ISO 1496-1 are only for unmodified shipping containers (Table A.7). The simulations of the unmodified container (M1) resulted in forces larger and smaller than those provided in ISO 1496-1. There are not any documents available to reference the structural strengths for modified containers. In order to account for the differences between the forces calculated from container model simulations and forces specified in ISO 1496-1, a comparison procedure was developed.

Once the unmodified container model (M1) reached yielding in Abaqus/CAE (2010), the applied force values were documented for each loading scenario. These calculated forces were compared to the forces presented in ISO 1496-1, and the ratio of the two values was calculated. The ratio value was used to multiply the modified container model's results to make them comparable to the values in ISO 1496-1. Table 7.2 presents the ratios used for each loading scenario and shows an example for Loading Scenario 1. The displacements for each container model were from the Abaqus/CAE (2010) simulations and were not adjusted.

Loading Scenario 1	Loading Scenario 2	Loading Scenario 3

Compressive Point Loading (4 corner fittings)	Compressive Point Loading (2 corner fittings short side)	Compressive Point Loading (2 corner fittings long side)
Loading Scenario 4	Loading Scenario 5

Transverse Point Loading (<i>Inward</i>)	Longitudinal Point Loading (<i>Inward</i>)	

Figure 7.1: Five Loading Scenarios Simulated on Shipping Container Models.

Door Header (near corner posts)	Front Corner Post (near base)	Side Base Rail (near corner posts)
Original	Original	Original

With Reinforcing Added	With Reinforcing Added	With Reinforcing Added

Figure 7.2: Additional Plate Reinforcing Examples.

Rear Corner Post and Door Header	Side Base Rail tied to Front Corner Post	Front Sill tied to Front Corner Post
Abnormal Stress Build Ups	Abnormal Stress Build Ups	Abnormal Stress Build Ups (Inside Container)

Added Reinforcing	Added Plate Reinforcing	Added Plate Reinforcing (Inside Container)

Figure 7.3: Abnormal Stress Build Up Locations and Solutions.

M1	M2	M3	M4

Original Container	Sidewalls Removed	Endwalls Removed	Roof Removed

M5	M6	M7	M8

Sidewalls and Endwalls Removed	Single Sidewall Removed	Single Endwall (Doors) Removed	Sidewalls, Endwalls, and Roof Removed

Figure 7.4: 20 ft ISO Shipping Container Modifications.

ABAQUS/CAE (2010) Warnings	Warning Explanations
WHENEVER A TRANSLATION (ROTATION) DOF AT A NODE IS CONSTRAINED BY A KINEMATIC COUPLING DEFINITION THE TRANSLATION (ROTATION) DOFS FOR THAT NODE CANNOT BE INCLUDED IN ANY OTHER CONSTRAINT INCLUDING MPCs, RIGID BODIES, ETC.	This was interpreted as any nodes used for a coupling constraint cannot be used for any tie constraints (this was discussed in Chapter 4).
SHELL NODE # INSTANCE # MET THE POSITION TOLERANCE FOR *SHELL TO SOLID COUPLING BUT ONLY ONE COUPLING NODE WAS FOUND. INCREASING THE VALUE OF THE INFLUENCE DISTANCE MAY BE NEEDED.	This was for the wall sections connecting into solid sections. More nodes on the wall's edge were needed to improve the constraint.
PLEASE MAKE SURE THAT THE MESH DENSITY OF THE SLAVE SURFACE IN THE TIE PAIR (#) IS FINER THAN THE MASTER SURFACE. THE ANALYSIS MAY RUN SLOWER, MAY YIELD INACCURATE RESULTS, AND MAY REQUIRE MORE MEMORY IF THIS IS NOT THE CASE.	The components which received this warning shared very similar mesh densities and this warning was seen as insignificant.
THE THICKNESS IS CONSIDERED BY DEFAULT IN THE TIED PAIR (#). TO IGNORE THICKNESS, SPECIFY THE 'NO THICKNESS' PARAMETER IN THE DEFINITION OF *TIE.	This was interpreted as the shell wall sections took their thickness into account for the model simulations.
SLAVE NODE # INSTANCE # WILL NOT BE TIED TO THE MASTER SURFACE #. THE DISTANCE FROM THE MASTER SURFACE IS GREATER THAN THE POSITION TOLERANCE VALUE.	This warning occurred for nodes outside a set distance for each connection and considered unimportant.
OVERCONSTRAINT CHECKS: NODE # INSTANCE # IS USED MORE THAN ONCE AS A SLAVE NODE IN THE *TIE KEYWORD. THE CONSTRAINT BETWEEN THIS NODE AND THE MASTER SURFACE WITH NODE # INSTANCE # IS REMOVED. CHECK IF THIS IS ACCEPTABLE.	There were nodes used for multiple connections at times, and Abaqus/CAE (2010) kept the node connected to one of the connections. This was generally not an issue for the container model, because the connections were robust and encompassed many nodes.

Table 7.1: Abaqus/CAE (2010) Warnings for Container Computer Simulations.

Figure 7.5: Maximum Applied Force and Displacement at Yielding for Loading Scenario 1 (*Slope of Line is Stiffness*).

Figure 7.6: Maximum Applied Force and Displacement at Yielding for Loading Scenario 2 (*Slope of Line is Stiffness*).

Figure 7.7: Maximum Applied Force and Displacement at Yielding for Loading Scenario 3 (Slope of Line is Stiffness).

Figure 7.8: Maximum Applied Force and Displacement at Yielding for Loading Scenario 4 (*Slope of Line is Stiffness*).

Figure 7.9: Maximum Applied Force and Displacement at Yielding for Loading Scenario 5 (*Slope of Line is Stiffness*).

	Abaqus/CAE (2010) Maximum Applied Force (N)	ISO 1496-1 (1990) Required Maximum Applied Force (N)	Ratio for Abaqus to ISO	
Loading Scenario 1 for M1	336641	942000	2.798	
Loading Scenario 2 for M1	378006	942000	2.492	
Loading Scenario 3 for M1	332088	942000	2.837	
Loading Scenario 4 for M1	298700	150000	0.502	
Loading Scenario 5 for M1	125000	75000	0.60	
<i>EXAMPLE:</i> Loading Scenario 1	Abaqus/CAE (2010) Maximum Applied Force (N)	ISO 1496-1 (1990) Required Maximum Applied Force (N)	Ratio for Abaqus to ISO	Maximum Applied Force Value (kN) <i>Abaqus * Ratio</i>
M1	336641	942000	2.798	942
M2	337960	unknown	2.798	942
M3	262670	unknown	2.798	735
M4	336675	unknown	2.798	942
M5	259179	unknown	2.798	725.2
M6	336675	unknown	2.798	942
M7	262670	unknown	2.798	735
M8	256373	unknown	2.798	717.3

Table 7.2: Ratio Example Comparing Abaqus/CAE (2010) and ISO 1496-1 Values.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 Summary

Chapter 8 presents a summary of the research, conclusions, and future research opportunities for shipping container buildings. The research reviewed container documents and information applicable for shipping container buildings. Multiple shipping container tables were created for classifications, structural considerations, and dimensions. Engineering building codes pertaining to shipping container housing were discussed, and container industry professionals were consulted. Foundations, connections, and reinforcing guidelines for shipping container buildings were discussed as well. Multiple finite element computer models of shipping containers were created and analyzed using the computer programs SolidWorks (2011), Hypermesh (2009), and Abaqus/CAE (2010). An optimized container model was modified into seven different container configurations. Five different loading scenario simulations were applied to each of the modified container models and analyzed, and comparisons between container modifications were discussed and presented.

8.2 Conclusions

The research aimed to produce a base point for using shipping containers for structural building applications. The conclusions learned from the research are:

- Most literature publicly available did not discuss modified shipping containers in detail and did not influence the research. The military shipping container documents were the most useful literature for investigating container modifications.
- Although convoluted at times, the ISO and CSC shipping container standards were the most reliable sources for container's specifications, structural strengths, serviceability, and applications.
- It was difficult to determine if the container manufacturers conformed to the structural ISO and CSC container standards correctly, because the container manufacturers were reluctant to disclose any structural test data on their shipping containers.
- Understanding how simple and complex modeled container elements interact was important to create an efficient model. Advice and guidance from professional finite element individuals is recommended to optimize the time and accuracy of the modeling process.
- For all loading scenarios, the calculated maximum elastic load for the complete model (M1) reached or exceeded the corresponding loads specified in ISO 1496-1 shown in Table A.7. With the exception of the roof removed model (M4) in Loading Scenario 5, the maximum resisting load for almost all the modified containers was either close or less

than the ISO 1496-1 specified loads. Therefore, it is likely that yielding may occur in modified containers before reaching the capacity required in ISO 1496-1.

- All of the container models yielded at the door header component when subjected to four vertical point loads (Loading Scenario 1). The endwalls under Loading Scenario 1 are the most critical load resisting components, and were more effective at carrying the loads than the sidewalls.
- All of the models except M7 (single endwall removed) first yielded at the front corner post where it was attached to the top corner fittings when subjected to two vertical point loads over the front wall (Loading Scenario 2). The sidewalls under Loading Scenario 2 are the most critical load resisting components, and the endwalls were somewhat effective at carrying the loads.
- All of the container models yielded at the door header component when subjected to two vertical point loads over the sidewall (Loading Scenario 3). The endwalls under Loading Scenario 3 are the most critical load resisting components. The sidewalls were also carrying significant load, especially in the absence of endwalls. The less stiff models were able to withstand larger applied forces, had larger displacements, and yielded in similar locations compared to the unmodified container model M1.
- The roof did not have any significant structural contribution when subjected to vertical point loads (Loading Scenarios 1, 2, and 3). When subjected to the vertical point loads from Loading Scenarios 2 and 3, the original container model M1 had lower maximum

applied forces compared to the other container models. When all four walls were present in the container model (M1 and M4), a localized yield stress in the door header may have occurred resulting in a reduced maximum applied force compared to the other container models.

- The endwalls subjected to Loading Scenario 4 (lateral loading on the short side of the container) were the critical lateral load resisting components. The lateral capacity of the sidewalls and roof components was very limited, and the roof component provided little resistance without wall components (models M5 and M8).
- The sidewalls under Loading Scenario 5 (lateral loading on the long side of the container) were the critical lateral load resisting components. Models containing both sidewalls and the roof (models M1 and M3) were the most rigid, and the container model without a roof (model M4) had a 66% maximum applied force increase and a 26% reduction in stiffness when compared to M1. The yield location changed when the roof was removed (M4) which may have caused the increase in maximum applied force for M4 (roof removed) when compared to the original container model M1.
- For axial/vertical loads applied on the top corner fittings, endwalls were generally the strongest load resisting components, the sidewalls were the next strongest load resisting components, and the roof typically did not have any structural contribution.
- For transverse lateral loads applied on the top corner fittings, the endwalls were the strongest load resisting components. For longitudinal lateral loads applied on the top

corner fittings, the sidewalls were the strongest load resisting components. The roof generally did not have any structural contribution for lateral loads.

8.3 Future Research Opportunities

The original research intended to discuss and analyze more regarding shipping containers for structural applications. However, certain topics and items were not covered. Future research needs to create a more detailed model (similar to the container model in Appendix C) which incorporates the door locking assembly (Figure C.17). Nonlinear and dynamic responses of the shipping container must be investigated, and the container and engineering industry must be consulted to improve modeling accuracy. Also, additional loading scenarios need to be considered such as uniform pressure loadings that can be applied on the wall surfaces. This research created a linear model that was analyzed under various load conditions. Technology was limited to run very detailed models as shown in Appendix C, and a significantly more accurate model and mesh could be created if the technology was available to develop and analyze the model.

Future research should investigate optimum modifications for shipping containers. This research originally aimed to develop a series of modified container orientations for specific scenarios. Depending on the end user of the research, the modified containers could be designed for disaster, military, or residential applications. Many of the modifications could be shared for different applications. Appropriate individuals and institutions must be consulted to provide scenarios and insight to ensure the modified container orientations developed are applicable and useful.

Once a series of modified containers are established, ensure the containers meet all the ISO structural test requirements. If a specific structural test was failed for a given modification, then it is necessary to find appropriate reinforcing options to strengthen the container. Future research can look into common materials found in different regions of the world which would be appropriate for container modifications. Availability, installation efficiency, cost, and applicability all effect which reinforcing options to use. Additional reinforcing can range from bamboo stalks to structural steel depending on what is available. Once the optimum reinforcing material is found, then future research can develop reinforcement guidelines for specific modified container orientations.

The research briefly discussed foundation design, but future research needs to provide an in depth foundation design for the optimum container orientations decided by individuals or institutions. A generic foundation design could be applicable for many soil types and locations. The foundations must be reviewed by a practicing structural engineer to ensure accuracy and applicability.

This research also originally aimed to provide insulation options for given container modifications. The insulation research can test common insulation options readily available for given temperatures and applications. Additional research should provide a more in depth discussion of common shipping container damage. Establishing which container damage, modifications, or defects are too dangerous to keep the container operational is necessary. Chapter 4 touched on this topic briefly, but a more comprehensive and definitive study is needed. This would also lead to the discussion on

the container's life span, and which containers are too old to be safely modified for building purposes.

Once the response of a given modified container is accurately simulated, full scale testing of the modified containers should be prepared. A full scale test of a modified shipping container for different loading scenarios will validate the computer simulations and data. All the publicly available documents have thus far (Chapter 2) only performed full scale testing for blast loading scenarios. Performing a full scale experiment on a modified shipping container is the most important item needed for shipping container research to progress accurately and confidently.

APPENDIX A

ISO SHIPPING CONTAINER TABLES

CONTAINER DESIGNATION	LENGTH (L)		WIDTH (W)		HEIGHT (H)		RATING (R)	
	Length	Tolerance	Width	Tolerance	Height	Tolerance	Mass	Weight
1EEE	45 ft (13716 mm)	0 -3/8 in. (10 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	9 ft- 6 in. (2896 mm)	0 -3/16 in. (5 mm)	30480 kg	67200 lb-f
1EE	45 ft (13716 mm)	0 -3/8 in. (10 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	8 ft- 6 in. (2591 mm)	0 -3/16 in. (5 mm)	30480 kg	67200 lb-f
1AAA	40 ft (12192 mm)	0 -3/8 in. (10 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	9 ft- 6 in. (2896 mm)	0 -3/16 in. (5 mm)	30480 kg	67200 lb-f
1AA	40 ft (12192 mm)	0 -3/8 in. (10 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	8 ft- 6 in. (2591 mm)	0 -3/16 in. (5 mm)	30480 kg	67200 lb-f
1A	40 ft (12192 mm)	0 -3/8 in. (10 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	30480 kg	67200 lb-f
1AX	40 ft (12192 mm)	0 -3/8 in. (10 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	< 8 ft (2438 mm)	~	30480 kg	67200 lb-f
1BBB	29 ft- 11.25 in. (9125 mm)	0 -3/8 in. (10 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	9 ft- 6 in. (2896 mm)	0 -3/16 in. (5 mm)	30480 kg	67200 lb-f
1BB	29 ft- 11.25 in. (9125 mm)	0 -3/8 in. (10 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	8 ft- 6 in. (2591 mm)	0 -3/16 in. (5 mm)	30480 kg	67200 lb-f
1B	29 ft- 11.25 in. (9125 mm)	0 -3/8 in. (10 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	30480 kg	67200 lb-f
1BX	29 ft- 11.25 in. (9125 mm)	0 -3/8 in. (10 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	< 8 ft (2438 mm)	~	30480 kg	67200 lb-f

Continued

Table A.1: External Dimensions, Tolerances, and Ratings (ISO 668, 1995).

Table A.1 Continued

CONTAINER DESIGNATION	LENGTH (L)		WIDTH (W)		HEIGHT (H)		RATING (R)	
	Length	Tolerance	Width	Tolerance	Height	Tolerance	Mass	Weight
1CC	19 ft- 10.5 in. (6058 mm)	0 -1/4 in. (6 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	8 ft- 6 in. (2591 mm)	0 -3/16 in. (5 mm)	30480 kg	67200 lb-f
1C	19 ft- 10.5 in. (6058 mm)	0 -1/4 in. (6 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	30480 kg	67200 lb-f
1CX	19 ft- 10.5 in. (6058 mm)	0 -1/4 in. (6 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	< 8 ft (2438 mm)	~	30480 kg	67200 lb-f
1D	9 ft- 9.75 in. (2991 mm)	0 -3/16 in. (5 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	10160 kg	22400 lb-f
1DX	9 ft- 9.75 in. (2991 mm)	0 -3/16 in. (5 mm)	8 ft (2438 mm)	0 -3/16 in. (5 mm)	< 8 ft (2438 mm)	~	10160 kg	22400 lb-f
NOTES: 1.) Rating (R) is the gross mass of a container which is both the maximum mass for operation and the minimum mass for testing. 2.) The table is updated to meet ISO 668: Amds.1-2 (2005).								

FREIGHT CONTAINER DESIGNATION	Minimum Unobstructed Internal Dimensions			Minimum Door Opening Dimensions	
	Length	Width	Height	Height	Width
1EEE	44 ft- 5.156 in. (13542 mm)	7 ft- 7.75 in. (2330 mm)	8 ft- 8.5 in. (2655 mm)	8 ft- 5 in. (2566 mm)	7 ft- 6 in. (2286 mm)
1EE	44 ft- 5.156 in. (13542 mm)	7 ft- 7.75 in. (2330 mm)	7 ft- 8.5in. (2350 mm)	7 ft- 5 in. (2261 mm)	7 ft- 6 in. (2286 mm)
1AAA	39 ft- 4.375 in. (11998 mm)	7 ft- 7.75 in. (2330 mm)	8 ft- 8.5 in. (2655 mm)	8 ft- 5 in. (2566 mm)	7 ft- 6 in. (2286 mm)
1AA	39 ft- 4.375 in. (11998 mm)	7 ft- 7.75 in. (2330 mm)	7 ft- 8.5in. (2350 mm)	7 ft- 5 in. (2261 mm)	7 ft- 6 in. (2286 mm)
1A	39 ft- 4.375 in. (11998 mm)	7 ft- 7.75 in. (2330 mm)	7 ft- 2.5in. (2197 mm)	7 ft (2134 mm)	7 ft- 6 in. (2286 mm)
1BBB	29 ft- 3.625 in. (8931 mm)	7 ft- 7.75 in. (2330 mm)	8 ft- 8.5 in. (2655 mm)	8 ft- 5 in. (2566 mm)	7 ft- 6 in. (2286 mm)
1BB	29 ft- 3.625 in. (8931 mm)	7 ft- 7.75 in. (2330 mm)	7 ft- 8.5in. (2350 mm)	7 ft- 5 in. (2261 mm)	7 ft- 6 in. (2286 mm)
1B	29 ft- 3.625 in. (8931 mm)	7 ft- 7.75 in. (2330 mm)	7 ft- 2.5in. (2197 mm)	7 ft (2134 mm)	7 ft- 6 in. (2286 mm)
1CC	19 ft- 3 in. (5867 mm)	7 ft- 7.75 in. (2330 mm)	7 ft- 8.5in. (2350 mm)	7 ft- 5 in. (2261 mm)	7 ft- 6 in. (2286 mm)
1C	19 ft- 3 in. (5867 mm)	7 ft- 7.75 in. (2330 mm)	7 ft- 2.5in. (2197 mm)	7 ft (2134 mm)	7 ft- 6 in. (2286 mm)
1D	9 ft- 2.3125 in. (2802 mm)	7 ft- 7.75 in. (2330 mm)	7 ft- 2.5in. (2197 mm)	7 ft (2134 mm)	7 ft- 6 in. (2286 mm)
NOTE:					
1.) The table is updated to meet ISO 668: Amds.1-2 (2005) and ISO 1496-1: Amds.1-4 (2006).					

Table A.2: Internal and Door Opening Dimensions (ISO 668, 1995).

CONTAINER DESIGNATION	S	P	K ₁ max.	K ₂ max.
	Length: Centers of Corner Post Holes	Width: Centers of Corner Post Holes	K ₁ = D ₁ -D ₂ or D ₃ -D ₄	K ₁ = D ₅ -D ₆
1EEE	44 ft- 3.875 in. (13509 mm)	7 ft- 4.969 in. (2259 mm)	0.75 in. (19 mm)	0.375 in. (10 mm)
1EE				
1AAA	39 ft- 3.875 in. (11985 mm)	7 ft- 4.969 in. (2259 mm)	0.75 in. (19 mm)	0.375 in. (10 mm)
1AA				
1A				
1AX				
1BBB	29 ft- 3.125 in. (8918 mm)	7 ft- 4.969 in. (2259 mm)	0.625 in. (16 mm)	0.375 in. (10 mm)
1BB				
1B				
1BX				
1CC	19 ft- 2.438 in. (5853 mm)	7 ft- 4.969 in. (2259 mm)	0.5 in. (13 mm)	0.375 in. (10 mm)
1C				
1CX				
1D	9 ft-1.719 in. (2787mm)	7 ft- 4.969 in. (2259 mm)	0.375 in. (10 mm)	0.375 in. (10 mm)
1DX				
NOTE: 1.) The table is updated to meet ISO 668: Amds.1-2 (2005).				

Table A.3: Center-to-Center distances between Corner Fittings and Diagonal Tolerances (ISO 668, 1995).

Figure A.1: ISO Shipping Container Dimensions Reference (ISO 668, 1995).

Size-Code First Character	Container Length
1	10 ft (2991 mm)
2	20 ft (6068 mm)
3	30 ft (9125 mm)
4	40 ft (12192 mm)
8	35 ft (10668 mm)
9	45 ft (13716 mm)
A	23 ft- 5 ½ in. (7150 mm)
B	24 ft (7315 mm)
C	24 ft- 4.5 in. (7430 mm)
D	24 ft- 5.3 in. (7450 mm)
E	25 ft- 7.87 in. (7820 mm)
F	26 ft- 6.9 in. (8100 mm)
G	41 ft (12500 mm)
H	43 ft (13106 mm)
K	44 ft- 7.43 in. (13600 mm)
L	45 ft (13716 mm)
M	48 ft (14630 mm)
N	49 ft (14935 mm)
P	53 ft (16154 mm)

This Container is a 45 ft x 8ft x 9.5 ft with passive vents at the upper part of cargo space

Size-Code Second Character	Container Height	Container Width
0	8 ft (2438 mm)	8 ft (2438 mm)
1	8 ft (2438 mm)	8 ft (2438 mm)
2	8 ft- 6 in. (2591 mm)	8 ft (2438 mm)
3	8 ft- 6 in. (2591 mm)	8 ft (2438 mm)
4	9 ft (2743 mm)	8 ft (2438 mm)
5	9 ft- 6 in. (2896 mm)	8 ft (2438 mm)
6	> 9ft- 6 in. (2896 mm)	8 ft (2438 mm)
7	4 ft- 4 in. (1310 mm)	8 ft (2438 mm)
8	4 ft- 3 in. (1295 mm)	8 ft (2438 mm)
9	≤ 4ft (1219 mm)	8 ft (2438 mm)

Continued

Table A.4: Size Code Character Definitions for ISO Containers (ISO 6346, 1995).

Table A.4 Continued

Size-Code Second Character	Container Height	Container Width
C	8 ft- 6 in. (2591 mm)	8ft (2438 mm) < width ≤ 8.2 ft (2500 mm)
D	9 ft (2743 mm)	8ft (2438 mm) < width ≤ 8.2 ft (2500 mm)
E	9 ft- 6 in. (2895 mm)	8ft (2438 mm) < width ≤ 8.2 ft (2500 mm)
F	> 9ft- 6 in. (2895 mm)	8ft (2438 mm) < width ≤ 8.2 ft (2500 mm)
L	8 ft- 6 in. (2591 mm)	width > 8.2 ft (2500 mm)
M	9 ft (2743 mm)	width > 8.2 ft (2500 mm)
N	9 ft- 6 in. (2895 mm)	width > 8.2 ft (2500 mm)
P	> 9ft- 6 in. (2895 mm)	width > 8.2 ft (2500 mm)
<p>NOTE:</p> <p>1.) The tables combine ISO 6346 (1984-1995). If a specific number or letter between the Second (1984) and Third (1995) editions had different values, the 1995 edition's value was used.</p> <p>2.) Highlighted sections are commonly used container specifications.</p>		

Type-Code Designation	Description
A0	Air/surface container
B0 or 80	Nonpressurized, box type, closed (Dry Bulk)
B1	Nonpressurized, box type, airtight (Dry Bulk)
B3	Pressurized, horizontal discharge, test pressure 150kPa (Dry Bulk)
B4	Pressurized, horizontal discharge, test pressure 265kPa (Dry Bulk)
B5	Pressurized, tipping discharge, test pressure 150 kPa (Dry Bulk)
B6	Pressurized, tipping discharge, test pressure 265kPa (Dry Bulk)
G0 or 00	Opening(s) at one end or both ends
G1 or 10	Passive vents at upper part of cargo space
G2 or 01	Opening(s) at one or both ends plus “full” opening(s) on one or both sides
G3 or 02	Opening(s) at one or both ends plus “partial” opening(s) on one or both sides
H0 or 40	Refrigerated and/or heated, with removable equipment located externally; heat transfer coefficient $K=0.4W/(m^2*K)$
H1 or 41	Refrigerated and/or heated with removable equipment located internally
H2 or 42	Refrigerated and/or heated with removable equipment located externally; heat transfer coefficient $K=0.7W/(m^2*K)$
H5	Insulated; heat transfer coefficient $K=0.4W/(m^2*K)$
H6	Insulated; heat transfer coefficient $K=0.7W/(m^2*K)$
P0 or 60	Incomplete superstructure, Platform (container)
P1 or 61	Fixed, two complete and fixed ends
P2 or 62	Fixed, fixed posts, either free-standing or with removable top member
P3 or 63	Folding (collapsible), folding complete end structure
P4 or 64	Folding (collapsible), Folding posts, either free-standing or with removable top member
P5 or 67	Complete superstructure, Open top, open ends (skeletal)
R0 or 31	Refrigerated, mechanically refrigerated
R1 or 32	Refrigerated and heated, mechanically refrigerated and heated
R2	Self-powered refrigerated/heated, mechanically refrigerated
R3	Self-powered refrigerated/heated, mechanically refrigerated and heated
S0 or 25	Livestock carrier
S1 or 26	Automobile carrier
S2	Live fish carrier

Continued

Table A.5: Type Code Character Definitions for ISO Containers (ISO 6346, 1984-1995).

Table A.5 Continued

Type-Code Designation	Description
T0 or 70	For non dangerous liquids, minimum pressure 45 kPa
T1 or 71	For non dangerous liquids, minimum pressure 150 kPa
T2 or 72	For non dangerous liquids, minimum pressure 265 kPa
T3 or 73	For dangerous liquids, minimum pressure 150 kPa
T4 or 74	For dangerous liquids, minimum pressure 265 kPa
T5 or 75	For dangerous liquids, minimum pressure 400 kPa
T6 or 76	For dangerous liquids, minimum pressure 600 kPa
T7	For gases, minimum pressure 910 kPa
T8 or 78	For gases, minimum pressure 2200 kPa
T9 or 79	For gases, minimum pressure (to be decided)
U0 or 50	Opening(s) at one or both ends
U1 or 51	Opening(s) at one or both ends, plus removable top member(s) in end frame(s)
U2 or 52	Opening(s) at one or both ends, plus opening(s) on one or both sides
U3 or 53	Opening(s) at one or both ends, plus opening(s) on one or both sides plus removable top member(s) in end frame(s)
U4	Opening(s) at one or both ends, plus partial opening on one side and full opening on the other side
U5	Complete, fixed side and end walls (no doors)
V0 or 13	Nonmechanical system, vents at lower and upper parts of cargo space
V2 or 15	Mechanical ventilation system, located internally
V4 or 17	Mechanical ventilation system, located externally

SIZE CODE	CAN STACK ON (Corner Posts Aligned) SIZE CODE	NOTES
10 through 19	10 through 19	~
1C, 1D, 1E, 1F	1C, 1D, 1E, 1F	Check External Width: 8 ft < Width ≤ 8.2 ft
1L, 1M, 1N, 1P	1L, 1M, 1N, 1P	Check External Width: 8.2 ft < Width
20 through 29	20 through 29	~
2C, 2D, 2E, 2F	2C, 2D, 2E, 2F	Check External Width: 8 ft < Width ≤ 8.2 ft
2L, 2M, 2N, 2P	2L, 2M, 2N, 2P	Check External Width: 8.2 ft < Width
30 through 39	30 through 39	~
3C, 3D, 3E, 3F	3C, 3D, 3E, 3F	Check External Width: 8 ft < Width ≤ 8.2 ft
3L, 3M, 3N, 3P	3L, 3M, 3N, 3P	Check External Width: 8.2 ft < Width
40 through 49	40 through 49, L0 through L9, M0 through M9, N0 through N9, P0 through P9	~
4C, 4D, 4E, 4F	4C, 4D, 4E, 4F, LC, LD, LE, LF, LL, MC, MD, ME, MF, NC, ND, NE, NF, PC, PD, PE, PF	Check External Width: 8 ft < Width ≤ 8.2 ft
4L, 4M, 4N, 4P	4L, 4M, 4N, 4P, LL, LM, LN, LP, ML, MM, MN, MP, NL, NM, NN, NP, PL, PM, PN, PP	Check External Width: 8.2 ft < Width
80 through 89	80 through 89	~

Continued

Table A.6: ISO Container Stacking Compatibility Chart Using Size Code Only
(Reference Table A.4 for Size Code Dimension Definitions).

Table A.6 Continued

SIZE CODE	CAN STACK ON (Corner Posts Aligned) SIZE CODE	NOTES
8C, 8D, 8E, 8F	8C, 8D, 8E, 8F	Check External Width: 8 ft < Width ≤ 8.2 ft
8L, 8M, 8N, 8P	8L, 8M, 8N, 8P	Check External Width: 8.2 ft < Width
A0 through A9	A0 through A9	~
AC, AD, AE, AF	AC, AD, AE, AF	Check External Width: 8 ft < Width ≤ 8.2 ft
AL, AM, AN, AP	AL, AM, AN, AP	Check External Width: 8.2 ft < Width
B0 through B9	B0 through B9	~
BC, BD, BE, BF	BC, BD, BE, BF	Check External Width: 8 ft < Width ≤ 8.2 ft
BL, BM, BN, BP	BL, BM, BN, BP	Check External Width: 8.2 ft < Width
C0 through C9	C0 through C9	~
CC, CD, CE, CF	CC, CD, CE, CF	Check External Width: 8 ft < Width ≤ 8.2 ft
CL, CM, CN, CP	CL, CM, CN, CP	Check External Width: 8.2 ft < Width
D0 through D9	D0 through D9	~
DC, DD, DE, DF	DC, DD, DE, DF	Check External Width: 8 ft < Width ≤ 8.2 ft
DL, DM, DN, DP	DL, DM, DN, DP	Check External Width: 8.2 ft < Width
E0 through E9	E0 through E9	~
EC, ED, EE, EF	EC, ED, EE, EF	Check External Width: 8 ft < Width ≤ 8.2 ft
EL, EM, EN, EP	EL, EM, EN, EP	Check External Width: 8.2 ft < Width
F0 through F9	F0 through F9	~
FC, FD, FE, FF	FC, FD, FE, FF	Check External Width: 8 ft < Width ≤ 8.2 ft

Continued

Table A.6 Continued

SIZE CODE	CAN STACK ON (Corner Posts Aligned) SIZE CODE	NOTES
FL, FM, FN, FP	FL, FM, FN, FP	Check External Width: 8 .2 ft< Width
G0 through G9	G0 through G9	~
GC, GD, GE, GF	GC, GD, GE, GF	Check External Width: 8 ft< Width ≤ 8.2 ft
GL, GM, GN, GP	GL, GM, GN, GP	Check External Width: 8 .2 ft< Width
H0 through H9	H0 through H9	~
HC, HD, HE, HF	HC, HD, HE, HF	Check External Width: 8 ft< Width ≤ 8.2 ft
HL, HM, HN, HP	HL, HM, HN, HP	Check External Width: 8 .2 ft< Width
K0 through K9	K0 through K9	~
KC, KD, KE, KF	KC, KD, KE, KF	Check External Width: 8 ft< Width ≤ 8.2 ft
KL, KM, KN, KP	KL, KM, KN, KP	Check External Width: 8 .2 ft< Width
L0 through L9	L0 through L9	~
LC, LD, LE, LF	LC, LD, LE, LF	Check External Width: 8 ft< Width ≤ 8.2 ft
LL, LM, LN, LP	LL, LM, LN, LP	Check External Width: 8 .2 ft< Width
M0 through M9	M0 through M9	~
MC, MD, ME, MF	MC, MD, ME, MF	Check External Width: 8 ft< Width ≤ 8.2 ft
ML, MM, MN, MP	ML, MM, MN, MP	Check External Width: 8 .2 ft< Width
N0 through N9	N0 through N9	~
NC, ND, NE, NF	NC, ND, NE, NF	Check External Width: 8 ft< Width ≤ 8.2 ft
NL, NM, NN, NP	NL, NM, NN, NP	Check External Width: 8 .2 ft< Width
P0 through P9	P0 through P9	~

Continued

Table A.6 Continued

SIZE CODE	CAN STACK ON (Corner Posts Aligned) SIZE CODE	NOTES
PC, PD, PE, PF	PC, PD, PE, PF	Check External Width: 8 ft < Width ≤ 8.2 ft
PL, PM, PN, PP	PL, PM, PN, PP	Check External Width: 8.2 ft < Width

Containers Considered in this Research using ISO 1496-1:	
<ul style="list-style-type: none"> · Standard General Purpose 40 ft and 20 ft ISO containers · With Size code (Table A.4): 22, 23, 45 · With Type code (Table A.5): G0, G1, 00, 10 	
Terms and Values Used (See Appendix B for values):	
R= Rating = 30480 kg (67200 lbf) g= Gravity = 9.81 m/s ² and (32.2 ft/s ²) T= Tare =2255 kg (4970 lbf) for 20 ft and 3920 kg (8645 lbf) for 40 ft P= Payload = R - T	
Structural Considerations:	
<ul style="list-style-type: none"> · All the tests presented are found in ISO 1496-1 and are updated from the five ISO 1496-1 amendments (ISO 1496-1: Amds. 1-5,1990-2006) · The reaction forces on each container exclude the reduction of the Tare weight · Container is fixed to ground by bottom faces of all four bottom corner fittings · All scenarios apply to both 20 ft and 40 ft containers unless labeled · No permanent deformation is allowed under loadings · The base structure cannot deflect more than 6 mm <i>below</i> the bottom faces of the lower corner fittings · The sum of length changes of the diagonals (D5 and D6, Figure A.1) cannot exceed 60 mm when container is transversely loaded · The container cannot deflect more than 25 mm in the longitudinal direction (top of container with respect to bottom of container) 	
Continued	

Table A.7 : Structural Tests for ISO Shipping Containers from ISO 1496-1 (ISO 1496-1, 1990).

Table A.7 Continued

Test Number	Test Load (ISO)	Test Load (CSC)	Test Load (Manufacturer)	Method
1.) Stacking	<i>Internal Load:</i> 1.8R-T <i>Testing load:</i> 96000 kg/post	<i>Internal Load:</i> 1.8R-T <i>Testing load:</i> 96000 kg/post	<i>Internal Load:</i> 1.8R-T <i>Testing load:</i> 97,200 or 86,400 kg/post	Hydraulic cylinder load to corner post through top corner fittings (Offset loading 25 mm laterally and 38 mm longitudinally) Time duration: 5 mins.
2.) Lifting from Top Corner Fittings	<i>Internal Load:</i> 2R-T	<i>Internal Load:</i> 2R-T	<i>Internal Load:</i> 2R-T	Lifting vertically from top corner fittings. Time duration: 5 mins.
3.) Lifting from Bottom Corner Fittings	<i>Internal Load:</i> 2R-T	None	<i>Internal Load:</i> 2R-T	Lifting at 30 deg. (40 ft container) and 37 deg. (20 ft container) from bottom corner fittings. Time duration: 5 mins.
4.) Restraint (Longitudinal)	<i>Testing Load:</i> 2R(R/side) <i>Internal Load:</i> R-T	<i>Testing Load:</i> 2R(R/side) <i>Internal Load:</i> R-T	<i>Testing Load:</i> 2R(R/side) <i>Internal Load:</i> R-T	Hydraulic cylinder load applied to bottom side rails in compression & then tension. Time duration: 5 mins.
5.) Wall Strength (Front & Door)	<i>Test Load:</i> 0.4 P	<i>Test Load:</i> 0.4 P (Check Safety Approval Plate)	<i>Test Load:</i> 0.4 P	Compressed air bag is used. Time duration: 5 mins.
6.) Side Wall Strength	<i>Test Load:</i> 0.6 P	<i>Test Load:</i> 0.6 P (Check Safety Approval Plate)	<i>Test Load:</i> 0.6 P	Compressed air bag is used. Time duration: 5 mins.

Continued

Table A.7 Continued

Test Number	Test Load (ISO)	Test Load (CSC)	Test Load (Manufacturer)	Method
7.) Roof Strength	<i>Test Load:</i> 300 kg	<i>Test Load:</i> 300 kg	<i>Test Load:</i> 300 kg	Applied loading will be the weakest place on an area 600 mm x 300 mm (longitudinal & transverse). Time duration: 5 mins.
8.) Floor Strength	<i>Truck Load:</i> 7,260 kg	<i>Truck Load:</i> 5460 kg	<i>Truck Load:</i> 7,260 kg	Special Truck Used. Total contact area: 284 cm ² , Wheel width: 180 mm, Wheel center distance: 760 mm
9.) Rigidity (Transverse)	<i>Test Force:</i> 15,240 kg (150 kN)	Not Specified	<i>Test Force:</i> 15,240 kg (150 kN)	Hydraulic cylinder will be applied to front header & door header through top corner fittings, in compression & then tension. Time duration: 5 mins.
10.) Rigidity (Longitudinal)	<i>Test Force:</i> 7,620 kg (75 kN)	None	<i>Test Force:</i> 7,620 kg (75 kN)	Hydraulic cylinder load will applied to side top rail through top corner fittings. Time duration: 5 mins.
11.) Lifting from Fork Pocket	<i>Internal Load:</i> 1.6R-T	None	<i>Internal Load:</i> 1.6R-T	Lifted by horizontal bars. Bar length: 1828 mm, Bar width: 200 mm, Time duration: 5 mins.
13.) Weather Proof test	Nozzle: 12.5 mm (inside dia.) - Distance: 1.5 m Pressure: 100 kpa (1 kg/cm ²) - Speed: 100 mm/Sec. (Not in CSC)			

Continued

Table A.7 Continued

Continued

Table A.7 Continued

<div data-bbox="262 370 380 511"> <div>299 kN (67.2 kip)</div> <div>75 kN (16.8 kip)</div> </div> <div data-bbox="388 386 772 483"> <p>FOR EACH LONGITUDINAL ARROW</p> <p>FOR EACH VERTICAL ARROW</p> </div> <div data-bbox="262 500 772 812"> <p>A 3D perspective diagram of a rectangular container. Red arrows point downwards from the top corners and outwards from the bottom corners along the longitudinal axis. A red dashed arrow points vertically upwards from the center of the bottom face.</p> </div> <div data-bbox="653 781 785 833"> <div>TEST 4</div> </div>	<div data-bbox="842 378 959 451"> <div>104 kN (23.4 kip)</div> </div> <div data-bbox="968 386 1339 438"> <p>FOR ARROW (DISTRIBUTED UNIFORMLY OVER EITHER END WALL)</p> </div> <div data-bbox="884 488 1283 764"> <p>A 3D perspective diagram of a rectangular container. The front end wall is shaded with red diagonal lines. A red arrow points horizontally from the center of this wall towards the interior of the container.</p> </div> <div data-bbox="953 789 1167 821"> <p>40 ft Container</p> </div> <div data-bbox="1220 781 1352 833"> <div>TEST 5</div> </div>	<div data-bbox="1409 378 1526 451"> <div>111 kN (25 kip)</div> </div> <div data-bbox="1535 386 1906 438"> <p>FOR ARROW (DISTRIBUTED UNIFORMLY OVER EITHER END WALL)</p> </div> <div data-bbox="1451 488 1850 764"> <p>A 3D perspective diagram of a rectangular container. The front end wall is shaded with red diagonal lines. A red arrow points horizontally from the center of this wall towards the interior of the container.</p> </div> <div data-bbox="1520 789 1734 821"> <p>20 ft Container</p> </div> <div data-bbox="1787 781 1919 833"> <div>TEST 5</div> </div>
<div data-bbox="262 862 380 935"> <div>156 kN (35 kip)</div> </div> <div data-bbox="388 873 772 925"> <p>FOR ARROW (DISTRIBUTED UNIFORMLY OVER EITHER SIDE WALL)</p> </div> <div data-bbox="317 967 716 1243"> <p>A 3D perspective diagram of a rectangular container. The right side wall is shaded with red diagonal lines. A red arrow points horizontally from the center of this wall towards the interior of the container.</p> </div> <div data-bbox="386 1276 600 1308"> <p>40 ft Container</p> </div> <div data-bbox="653 1268 785 1320"> <div>TEST 6</div> </div>	<div data-bbox="829 862 947 935"> <div>166 kN (37 kip)</div> </div> <div data-bbox="955 873 1327 925"> <p>FOR ARROW (DISTRIBUTED UNIFORMLY OVER EITHER SIDE WALL)</p> </div> <div data-bbox="884 967 1283 1243"> <p>A 3D perspective diagram of a rectangular container. The right side wall is shaded with red diagonal lines. A red arrow points horizontally from the center of this wall towards the interior of the container.</p> </div> <div data-bbox="953 1276 1167 1308"> <p>20 ft Container</p> </div> <div data-bbox="1220 1268 1352 1320"> <div>TEST 6</div> </div>	<div data-bbox="1396 862 1514 935"> <div>2.9 kN (0.7 kip)</div> </div> <div data-bbox="1535 862 1864 935"> <p>FOR ARROW (APPLIED AT CENTER OF ROOF DISTRIBUTED OVER AREA OF 600mm by 300mm)</p> </div> <div data-bbox="1451 967 1850 1268"> <p>A 3D perspective diagram of a rectangular container. The top roof surface is shaded with red diagonal lines. A red arrow points vertically downwards from the center of the roof.</p> </div> <div data-bbox="1787 1268 1919 1320"> <div>TEST 7</div> </div>

Continued

Table A.7 Continued

Splice:

- An acceptable splice on steel rails is *butt-welded, flush-fitting* and restores the original size and cross-sectional profile of the repaired component
- Splice is a minimum distance of 6 inches (150mm) long
- Minimum distance of 12 inches (300mm) between splice repairs
- If a splice would end within 12 inches (300mm) of another weld, such as at the juncture with the corner fitting, it must be extended to that weld.

Primary (main) structural components:

- Corner fittings, front and rear corner posts, door sill and header, front sill and header, top and bottom side rails, floor cross members, and forklift pockets.

Patch:

- Any repair of a wall, roof, or door panel that adds or replaces material without complete replacement of the panel.
- A patch may be either an insert or overlapping type of repair.
- Lap-welded patches should overlap existing panel by at least 1/2 inch (13mm). Riveted patches should overlap existing panel by at least 2 inches (50mm). Butt-welded patches should be flush fitting.

Continued

Table A.8: ISO Shipping Container Damage Table (Department of Defense, 2002).

Table A.8 Continued

	Corner Fittings	Corner Post	Door Header	Door Sill
Dent or Bend	Not Allowed	> 19 mm (.75 in) depth regardless of length	> 32 mm (1.25 in) depth regardless of length	> 40 mm (1.5625 in) depth regardless of length
Crack, Break, Cut, Tear, Hole, Puncture, or Corrosive	Not Allowed	Not Allowed	Not Allowed	Not Allowed
Defective, Cracked, or Broken Weld	Not Allowed	At juncture with Corner Fitting	At juncture between any primary structural components	At juncture between any primary structural components
Deformation or Bow	Not Allowed	Exceeds Tolerances given in Table A.3	Exceeds Tolerances given in Table A.3	Exceeds Tolerances given in Table A.3
Splice	Not Allowed	·Extends through/across more than 1/2 the cross-sectional profile of the post. ·More than 2 splices or improper splice.	Improper Splice. Cannot interfere with door hardware	Improper Splice. Cannot interfere with door hardware
Gaps	~	~	~	~
Hardware	~	~	~	~

Continued

Table A.8 Continued

	Front Header	Front Sill	Top Side Rail	Bottom Side Rail
Dent or Bend	> 32 mm (1.25 in) depth regardless of length	> 40 mm (1.5625 in) depth regardless of length	> 32 mm (1.25 in) depth regardless of length	> 40 mm (1.5625 in) depth regardless of length. In Web, within 10mm of corner fitting, > 19 mm (.75 in) depth regardless of length
Crack, Break, Cut, Tear, Hole, Puncture, or Corrosive	Not Allowed	Not Allowed	Not Allowed	Not Allowed
Defective, Cracked, or Broken Weld	At juncture between any primary structural components	At juncture between any primary structural components	At juncture between any primary structural components	At juncture between any primary structural components
Deformation or Bow	Exceeds Tolerances given in Table A.3	Exceeds Tolerances given in Table A.3	Exceeds Tolerances given in Table A.3	Exceeds Tolerances given in Table A.3
Splice	Improper Splice	Improper Splice	Improper Splice. Cannot interfere with door hardware	Improper Splice. Cannot interfere with door hardware
Gaps	~	~	~	~
Hardware	~	~	~	~

Continued

Table A.8 Continued

	Floor Cross Member	Side and End Wall Panels	Roof	Doors
Dent or Bend	> 25 mm (1 in) depth regardless of length. In flange, > 40 mm (1.5625 in) depth regardless of length	> 40 mm (1.5625 in) in any direction. Or Bulging extends past corner fitting	> 40 mm (1.5625 in) in any direction. Or Bulging extends past corner fitting	> 40 mm (1.5625 in) in any direction. Or Bulging extends past corner fitting
Crack, Break, Cut, Tear, Hole, Puncture, or Corrosive	Not Allowed	Not Allowed	Not Allowed	Not Allowed
Defective, Cracked, or Broken Weld	At juncture between any primary structural components	At juncture between any primary structural components	At juncture between any primary structural components	On anti-racking hardware
Deformation or Bow	Exceeds Tolerances given in Table A.3	~	~	~
Splice	Improper Splice. More than 2, improper, or full profile splices	~	~	~
Gaps	A separation between the top of a cross member and underside of the flooring that is greater than 10mm (3/8 in) at point of attachment	~	~	~
Hardware	~	~	~	Any seized, twisted, broken, missing, or otherwise inoperative door hardware

Structurally sensitive component	Serious structural deficiency
Top rail	Local deformation to the rail in excess of 60 mm or separation or cracks or tears in the rail material in excess of 45 mm in length. Note: On some designs of tank containers the top rail is not a structurally significant component.
Bottom rail	Local deformation perpendicular to the rail in excess of 100 mm or separation or cracks or tears in the rail's material in excess of 75 mm in length.
Header	Local deformation to the header in excess of 80 mm or cracks or tears in excess of 80 mm in length.
Sill	Local deformation to the sill in excess of 100 mm or cracks or tears in excess of 100 mm in length.
Corner posts	Local deformation to the post exceeding 50 mm or tears or cracks in excess of 50 mm in length.
Corner and intermediate fittings (Castings)	Missing corner fittings, any through cracks or tears in the fitting, any deformation of the fitting that precludes full engagement of securing or lifting fittings, any deformation of the fitting beyond 5 mm from its original plane, any aperture width greater than 66.0 mm, any aperture length greater than 127.0 mm, any reduction in thickness of the plate containing the top aperture that makes it less than 23.0 mm thick or any weld separation of adjoining components in excess of 50 mm in length.
Under structure	Two or more adjacent cross members missing or detached from the bottom rails. 20% or more of the total number of cross members are missing or detached. Note: If onward transportation is permitted, it is essential that detached cross members are precluded from falling free.
Locking rods	One or more inner locking rod is non-functional. Note: Some containers are designed and approved (and so recorded on the CSC Plate) to operate with one door open or removed.

Table A.9: CSC Damage Chart for All Containers (CSC, 2010).

APPENDIX B
SHIPPING CONTAINER DATABASE

The Shipping Container Database Chart does not contain the following:

- 1.) Shipping/freight containers without ISO corner fittings
- 2.) Tank, generator, or transformer shipping containers
- 3.) Flatrack containers without corner posts
- 4.) Shipping containers less than 8 ft wide
- 5.) Shipping containers used for construction/housing offices

Definitions for the Shipping Container Database Chart:

- 1.) **Size Code:** Boxed in Red

- 2.) **Type Code:** Circled in Yellow

- 3.) **Length (L):** The largest external distance of a container measured horizontally from one ISO corner fitting edge to another.
- 4.) **Width (W):** The second largest external distance of a container measured horizontally from one ISO corner fitting edge to another.
- 5.) **Height (H):** The largest external distance of a container measured vertically from the bottom of an ISO corner fitting to the top of an ISO corner fitting.
- 6.) **Max. Weight:** The Maximum Weight (Rating) is the heaviest the container will be when fully loaded. The Maximum Weight takes into account the weight of the goods, the weight of the container itself, and all additional components on the container. The Maximum Weight is displayed as a force (lbf) and a mass (kg). Lbf stands for pound-force and kg stands for kilograms.
- 7.) **Empty Weight:** The Empty Weight (Tare) is the weight of the container itself including additional components. The Empty Weight (Tare) was determined from averaging multiple shipping container manufacturers' specifications. The Empty Weight is displayed as a force (lbf) and a mass (kg).

8.) **Maximum Compressive Force Container Can Withstand:** The maximum compressive force each container can withstand before failure. The force is assumed to distribute evenly to each of the container's four corner posts. The values given are averaged from multiple shipping container manufacturers and modified if certain ISO criteria are met.

For non-ISO containers, Equation B.1 shows how the *Maximum Compressive Force* is calculated:

$$\text{Allowable Stacking Weight} \times 1.8 = \text{Max. Compressive Force} \quad (\text{B.1})$$

where *Allowable Stacking Weight* is given by container manufacturers. Sometimes, it is listed as *Allowable Stacking Weight (1.8g)* which means the containers were tested with a safety factor of 1.8, but the actual weight allowed to be applied to the containers is what is given as the *Allowable Stacking Weight (1.8g)* value. For ISO containers, Equation B.2 shows how the *Maximum Compressive Force* is calculated:

$$(\text{Allowable Stacking Weight} \times 1.8) + (\text{Maximum Weight} \times 1.8) - \text{Empty Weight} = \text{Max. Compressive Force} \quad (\text{B.2})$$

where *Maximum Weight* is given by container's Rating and the *Empty Weight* is the Tare weight of the container. The addition values account for internal loads during the stacking test in ISO 1496-1.

Instructions for Using the Shipping Container Database Chart:

1.) See if the Size and Type Codes are printed on the container then consult the Chart. The Size Code decreases alphabetically and then decreases numerically in the Chart. The Type Code generally increases alphabetically for a given Length (L).

2.) If Size and Type Codes are not available, then determine the Length (L) of the container. The Shipping Container Database Chart starts at largest Length (L) and decreases.

The Width (W) and Height (H) of the containers increase for a given Length (L).

3.) The pictures of containers are generally in order with the Size Code and Type Code for a given Length (L).

Notes for the Shipping Container Database Chart:

1.) When a container is listed as a ## ft container, it is assumed the container is ## ft in Length (L).

2.) Use Table A.4 and Table A.5 to define the Size and Type Codes.

3.) Any container with a shaded Size and Type Code is an ISO container which follows ISO 668 (1995) and ISO 1496-1 (1990) standards. This allows the container to withstand a larger compressive force.

4.) The manufacturers investigated for the Shipping Container Database Chart are explained in detail at the end of Appendix B.

5.) Do to the inconsistencies, lack of data, and quality control from the container manufacturers, use the *Maximum Compressive Force Container Can Withstand* values cautiously.

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
PN	R0, R1, 31, 32	53 ft (16154 mm)	8 ft- 6 in. (2591 mm)	9 ft- 6 in. (2896 mm)	85010 lbf (38560 kg)	15300 lbf (6940 kg)	306040 lbf (1361 kN)
PP	G0, G1, 00, 10	53 ft (16154 mm)	8 ft- 6 in. (2591 mm)	9 ft- 6 ½ in. (2908 mm)	85025 lbf (38565 kg)	11210 lbf (5085 kg)	241910 lbf (1076 kN)
PP	R0, R1, 31, 32	53 ft (16154 mm)	8 ft- 6 ¾ in. (2600 mm)	9 ft- 6 ½ in. (2908 mm)	85010 lbf (38560 kg)	12798 lbf (5805 kg)	128180 lbf (570 kN) Aluminum Container
						14110 lbf (6400 kg)	229855 lbf (1022 kN) Steel Container
						16094 lbf (7300 kg)	114765 lbf (510 kN) Aluminum Container with Fuel Tank on Underside

NOTES:

- Only stack and support 53 ft containers (Not an ISO container) on other 53 ft containers (Check Widths).
- Manufacturers of 53 ft containers: CIMC & SINGAMAS

Table B.1: 53 ft Shipping Containers.

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
?F	S1 or 26 (Six Car Transport)	50 ft- 6 ¹⁹ / ₆₄ in. (15400 mm)	8 ft- 2 ²⁷ / ₆₄ in. (2500 mm)	10 ft- 6 in. (3200mm)	67200 lbf (30480 kg)	23215 lbf (10530 kg)	604775 lbf (2690 kN)

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
M2 or M3	U1 or 51 (External Platform & Ladders on 1 End)	48 ft (14630 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	80470 lbf (36500 kg)	15047 lbf (6825 kg)	598230 lbf (2661 kN)
M4	U1 or 51 (External Platform and Ladders on 1 End)	48 ft (14630 mm)	8 ft (2438 mm)	9 ft (2743 mm)	91425 lbf (41470 kg)	14264 lbf (6470 kg)	362865 lbf (1614 kN)
M5	G0, G1, 00, 10	48 ft (14630 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	67200 lbf (30480 kg)	11244 lbf (5100 kg)	761920 lbf (3389 kN)
M6	G0, G1, 00, 10	48 ft (14630 mm)	8 ft (2438 mm)	9 ft- 10 in. (3000 mm)	70550 lbf (32000 kg)	11332 lbf (5140 kg)	?
ME	R0, R1, 31, 32 (Corner Fittings only at 48')	48 ft (14630 mm)	8 ft- 2 ²⁷ / ₆₄ in. (2500 mm)	9 ft- 6 in. (2896 mm)	77825 lbf (35300 kg)	11685 lbf (5300 kg)	?

NOTES:

- Stack 50 ft- 6 in. and 48 ft. containers (Not ISO containers) on containers no smaller than 48 ft in length (Check Widths).
- Manufacturers of 50 ft- 6 in. and 48 ft containers: CIMC, DFIC, & SINGAMAS

Table B.2: 48 ft to 51 ft Shipping Containers.

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
?N	R0, R1, 31, 32	46 ft - 6 ¹⁵ / ₃₂ in. (14185 mm)	8 ft - 2 ¹³ / ₁₆ in. (2510 mm)	9 ft- 6 in. (2896 mm)	70550 lbf (32000 kg)	15653 lbf (7100 kg)	253975 lbf (1130 kN)

NOTES:

- Stack 46 ft. - 6 ¹⁵/₃₂ in. containers on containers no smaller than 46 ft. - 6 ¹⁵/₃₂ in (Not an ISO container).
- Manufacturer of 46 ft.- 6 ¹⁵/₃₂ in. containers: CIMC

Table B.3: 46 ft to 47 ft Shipping Containers.

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
L2, L3 or 92, 93	R0, R1, 31, 32 (Internal Meat Hangers)	45 ft (13716 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	67200 lbf (30480 kg)	8642 lbf (3920 kg)	899500 lbf (4001 kN)
L5 or 95	G0, G1, 00, 10	45 ft (13716 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	71650 lbf (32500 kg)	10593 lbf (4805 kg)	975670 lbf (4340 kN) Stacking on 45' while supporting 45'
							492330 lbf (2190 kN) Stacking on 40' while supporting 40'
							492330 lbf (2190 kN) Stacking on 40' while supporting 45'
							370935 lbf (1650 kN) Stacking on 45' while supporting 40'
L5 or 95	P3, 63 (One Open Side Frame)	45 ft (13716 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	88185 lbf (40000 kg)	13120 lbf (5950 kg)	761920 lbf (3389 kN)
L5 or 95	R0, R1, 31, 32	45 ft (13716 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	67200 lbf (30480 kg)	15653 lbf (7100 kg)	?

NOTES:

- Stack and Support 45 ft containers on other 45 ft containers only, Unless stated otherwise.
- Manufacturers of 45 ft containers on This Page: CIMC, CXIC, DFIC, SINGAMAS, & SINO-PEAK

Continued

Table B.4: 45 ft Shipping Containers.

Table B.4 Continued

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
LE or 9E	G0, G1, 00, 10	45 ft (13716 mm)	8 ft- 2 ²⁷ / ₆₄ in. (2500 mm)	9 ft- 6 in. (2896 mm)	74960 lbf (34000 kg)	10340 lbf (4690 kg)	749860 lbf (3336 kN) Stacking on 45' while supporting 45'
							241910 lbf (1076 kN) All other stacking/support scenarios
LN or 9N	G2, U2, 01, 52 (Curtain Side Walls)	45 ft (13716 mm)	8 ft- 4 ²⁵ / ₆₄ in. (2550 mm)	9 ft- 6 in. (2896 mm)	74960 lbf (34000 kg)	13184 lbf (5980 kg)	725770 lbf (3228 kN)
LN or 9N	R0, R1, 31, 32	45 ft (13716 mm)	8 ft- 4 ⁵ / ₈ in. (2556 mm)	9 ft- 6 in. (2896 mm)	74960 lbf (34000 kg)	13206 lbf (5990 kg)	539700 lbf (2401 kN)
LN or 9N	R0, R1, 31, 32	45 ft (13716 mm)	8 ft- 6 in. (2591 mm)	9 ft- 6 in. (2896 mm)	74960 lbf (34000 kg)	13338 lbf (6050 kg)	761920 lbf (3389 kN) Stacking on 45' while supporting 45'
							362905 lbf (1614 kN) Stacking on 40' while supporting 40'
							362905 lbf (1614 kN) Stacking on 45' while supporting 40'
							241910 lbf (1076 kN) Stacking on 40' while supporting 45'
NOTES: <ul style="list-style-type: none"> Stack and Support 45 ft containers on other 45 ft containers only, Unless stated otherwise (Check Widths). Manufacturers of 45 ft containers on This Page: CIMC, SINGAMAS, & SINO-PEAK

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
HN	B0, B1, 80 (500mm Man Holes-Roof)	43 ft (13107 mm)	8 ft- 4 ²⁵ / ₆₄ in. (2550 mm)	9 ft- 6 in. (2896 mm)	77160 lbf (35000 kg)	13775 lbf (6250 kg)	?

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
?P	R0, R1, 31, 32 (Protection Frame)	41 ft- 3 in. (12573 mm)	8 ft - 2 ¹³ / ₁₆ in. (2510 mm)	9 ft- 10 in. (3000 mm)	70550 lbf (32000 kg)	15300 lbf (6940 kg)	253970 lbf (1130 kN)

NOTES:

- Stack and Support 43 ft containers on other 43 ft containers only (Not an ISO container).
- Stack and Support 41 ft- 3 in. containers on other 41 ft- 3 in. containers only (Not an ISO container).
- Manufacturer of 43 ft and 41 ft- 3 in. containers: CIMC

Table B.5: 41 ft to 43 ft Shipping Containers.

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAX. COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
42 or 43	G0, G1, 00, 10	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	67200 lbf (30480 kg)	8290 lbf (3760 kg)	898400 lbf (3996 kN)
42 or 43	G1,10 (Waste Container)	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	74850 lbf (33950 kg)	10582 lbf (4800 kg)	932500 lbf (4148 kN)
42 or 43	P3, 63	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	99210 lbf (45000 kg)	11300 lbf (5125 kg)	761920 lbf (3389 kN)
42 or 43	P3, 63 (One Open End Frame)	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	88185 lbf (40000 kg)	9700 lbf (4400 kg)	761920 lbf (3389 kN)
42 or 43	P3, 63 (Open End Walls)	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	99210 lbf (45000 kg)	10800 lbf (4900 kg)	761920 lbf (3389 kN)
42 or 43	P3, 63 (Extendable Posts to 10'-6")	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	110235 lbf (50000 kg)	11245 lbf (5100 kg)	857160 lbf (3813 kN)
42 or 43	P4, 64	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	99210 lbf (45000 kg)	11905 lbf (5400 kg)	?

NOTES:

- Stack and Support 40 ft containers on 40 ft or 45 ft containers.
- Manufacturers of 40 ft containers on This Page: BSL, CIMC, CXIC, DFIC, HUNG-DAO, SINGAMAS, SINO-PEAK, & RYC

Continued

Table B.6: 40 ft Shipping Containers.

Table B.6 Continued

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
42 or 43	R0, R1, 31, 32	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	67200 lbf (30480 kg)	9855 lbf (4470 kg)	761920 lbf (3389 kN)
42 or 43	R0, R1, 31, 32 (Separates into a 16' & 24' Container)	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	67200 lbf (30480 kg)	9920 lbf (4500 kg)	761920 lbf (3389 kN)
42 or 43	R? (Side Door)	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	67200 lbf (30480 kg)	11575 lbf (5250 kg)	0
42 or 43	U1, 51 (Soft Roof)	40 ft (12192 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	67200 lbf (30480 kg)	8675 lbf (3935 kg)	874210 lbf (3889 kN)

NOTES:

- Stack and Support 40 ft containers on 40 ft or 45 ft containers.
- Manufacturers of 40 ft containers on This Page: CIMC & SINGAMAS

Continued

Table B.6 Continued

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAX. COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
45	G0, G1, 00, 10	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	67200 lbf (30480 kg)	8645 lbf (3920 kg)	969475 lbf (4312 kN)
45	G3 or 02 (Side Door)	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	67200 lbf (30480 kg)	8600 lbf (3900 kg)	874280 lbf (3889 kN)
45	P2, 62	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	67200 lbf (30480 kg)	8000 lbf (3630 kg)	761920 lbf (3389 kN)
45	P3, 63	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	110235 lbf (50000 kg)	11575 lbf (5250 kg)	899500 lbf (4001 kN)
45	P3, 63 (One Gooseneck Tunnel)	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	115745 lbf (52500 kg)	11465 lbf (5200 kg)	857160 lbf (3813 kN)
45	P3, 63 (Two Gooseneck Tunnels)	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	74960 lbf (34000 kg)	12125 lbf (5500 kg)	761920 lbf (3389 kN)
45	P3, 63 (Two Gooseneck Tunnels)	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	99210 lbf (45000 kg)	12015 lbf (5450 kg)	899500 lbf (4001 kN)
45	P3, 63 (One Open End Frame & End Wall with Holes)	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	74960 lbf (34000 kg)	11795 lbf (5350 kg)	761920 lbf (3389 kN)
NOTES: <ul style="list-style-type: none"> Stack and Support 40 ft containers on 40 ft or 45 ft containers. Manufacturers of 40 ft containers on This Page: BSL, CIMC, CXIC, DFIC, HUNG-DAO, SINGAMAS, SINO-PEAK, & RYC 							

Continued

Table B.6 Continued

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAX. COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
45	P3, 63 (Posts reaching 13'-6"- diagonal bracing)	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	99210 lbf (45000 kg)	12345 lbf (5600 kg)	761920 lbf (3389 kN)
45	P3, 63 (Posts reaching 13'-6"- no diagonal bracing)	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	110235 lbf (50000 kg)	13230 lbf (6000 kg)	761920 lbf (3389 kN)
45	P4, 64	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	44095 lbf (20000 kg)	9920 lbf (4500 kg)	396835 lbf (1765 kN)
45	R0, R1, 31, 32	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	74960 lbf (34000 kg)	10065 lbf (4565 kg)	668270 lbf (2973 kN)
45	R0, R1, 31, 32 (Recessed Butcher Door)	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	67200 lbf (30480 kg)	11130 lbf (5050 kg)	37460 lbf (167 kN)
45	S0 or 25 (Animal Transport)	40 ft (12192 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	67200 lbf (30480 kg)	8910 lbf (4040 kg)	326555 lbf (1453 kN)
46	S1 or 26 (4 Car Transport)	40 ft (12192 mm)	8 ft (2438 mm)	10 ft- 2 ³ / ₆₄ in. (3100 mm)	67200 lbf (30480 kg)	13490 lbf (6100 kg)	761920 lbf (3389 kN)
4E	G0, G1, 00, 10	40 ft (12192 mm)	8 ft- ⁵⁵ / ₆₄ in. (2460 mm)	9 ft- 6 in. (2896 mm)	74960 lbf (34000 kg)	9425 lbf (4275 kg)	621445 lbf (2764 kN)
4E	R? (Side Door)	40 ft (12192 mm)	8 ft- 2 ¹ / ₃₂ in. (2490 mm)	9 ft- 6 in. (2896 mm)	52910 lbf (24000 kg)	12125 lbf (5500 kg)	95240 lbf (424 kN)

NOTES:

- Stack and Support 40 ft containers on 40 ft or 45 ft containers (Check Widths).
- Manufacturers of 40 ft containers on This Page: CIMC & SINGAMAS

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
3M	B0, 80	29 ft- 11 ¹ / ₄ in. (9125 mm)	8 ft- 4 ²⁵ / ₆₄ in. (2550 mm)	9 ft (2743 mm)	74960 lbf (34000 kg)	6700 lbf (3040 kg)	404770 lbf (1801 kN)

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
EP	R0, R1, 31, 32 (Swapbody)	25 ft- 7 ⁵⁵ / ₆₄ in. (7820 mm)	8 ft- 4 ²⁵ / ₆₄ in. (2550 mm)	9 ft-11 ¹⁹ / ₆₄ in. (3030 mm)	39865 lbf (18000 kg)	9480 lbf (4300 kg)	71430 lbf (318 kN)
EP	R0, R1, 31, 32 (Swapbody)	25 ft- 7 ⁵⁵ / ₆₄ in. (7820 mm)	8 ft- 2 ⁶³ / ₆₄ in. (2514 mm)	9 ft- 10 ⁷ / ₆₄ in. (3000 mm)	39865 lbf (18000 kg)	9480 lbf (4300 kg)	71430 lbf (318 kN)

NOTES:

- Stack and Support 29 ft- 11 ¹/₄ in. containers on other 29 ft- 11 ¹/₄ in. containers only (Not an ISO container).
- Stack and Support 25 ft- 7 ⁵⁵/₆₄ in. (Not an ISO container) containers on other 25 ft- 7 ⁵⁵/₆₄ in. containers only (Check Widths).
- Manufacturers of 29 ft- 11 ¹/₄ in. and 25 ft- 7 ⁵⁵/₆₄ in. containers: CIMC & CXIC

Table B.7: 25 ft to 30 ft Shipping Containers.

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
D5	G0, G1, 00, 10	24 ft- 5 ⁵ / ₁₆ in. (7450 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	52910 lbf (24000 kg)	7187 lbf (3260 kg)	190480 lbf (847 kN)
D?	G0, G1, 00, 10 (Swapbody)	24 ft- 5 ⁵ / ₁₆ in. (7450 mm)	8 ft- 4 ²⁵ / ₆₄ in. (2550 mm)	8 ft- 11 ³¹ / ₆₄ in. (2730 mm)	35275 lbf (16000 kg)	6614 lbf (3000 kg)	51590 lbf (229 kN)

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SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
?P	G0, G1, 00, 10 (Doors: 2 Full Ventiladed Sides)	20 ft (6100 mm)	8 ft- 2 ¹ / ₂ in. (2502 mm)	9 ft- 10 in. (2997 mm)	62700 lbf (30480 kg)	9524 lbf (4320 kg)	217700 lbf (968 kN)

NOTES:

- Stack and Support 24 ft- 5 ⁵/₁₆ in. (Not an ISO container) containers on other 24 ft- 5 ⁵/₁₆ in. containers only (Check Widths).
- Stack and Support 20 ft containers on other 20ft containers only (Not an ISO container).
- Manufacturer of 24 ft- 5 ⁵/₁₆ in. and 20 ft containers: CIMC

Table B.8: 20 ft to 25 ft Shipping Containers.

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAX. COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
20 or 21	B0, 80 (Pneumatic Roof, Loading Hatches- No Doors)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft (2438 mm)	62700 lbf (30480 kg)	8070 lbf (3660 kg)	967640 lbf (4304 kN)
20 or 21	G2, U2, 01, 52 (Doors: 2 Full Side & 2 Sideways Ends)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft (2438 mm)	24000 lbf (10886 kg)	8375 lbf (3800 kg)	796745 lbf (3544 kN)
20 or 21	G3 or 02 (Doors: 1 Partial Side & 2 End)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft (2438 mm)	52910 lbf (24000 kg)	5512 lbf (2500 kg)	851645 lbf (3788 kN)
20 or 21	U5 (No Doors & Removable Hard Roof)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft (2438 mm)	62700 lbf (30480 kg)	7100 lbf (3220 kg)	770020 lbf (3425 kN)
22 or 23	B0, 80 (2 Rectangular Discharge Doors at Ends)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	52910 lbf (24000 kg)	5605 lbf (2543 kg)	761920 lbf (3389 kN)
22 or 23	G0, G1, 00, 10	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	62700 lbf (30480 kg)	4970 lbf (2255 kg)	925530 lbf (4117 kN)
22 or 23	G0, G1, 00, 10 (Two Rectangular Top Hatches)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	62700 lbf (30480 kg)	6830 lbf (3100 kg)	496670 lbf (2209 kN)
22 or 23	G1 or 10 (Waste Container with External Stiffeners)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	52910 lbf (24000 kg)	9810 lbf (4450 kg)	847345 lbf (3769 kN)
NOTES: <ul style="list-style-type: none"> Stack and Support 20 ft containers on 20 ft containers. Manufacturers of 20 ft containers on This Page: BSL, CIMC, CXIC, DFIC, HUNG-DAO, SINGAMAS, SINO-PEAK, & RYC 							

Continued

Table B.9: 20 ft Shipping Containers.

Table B.9 Continued

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
22 or 23	G2, U2, 01, 52 (Doors: 1 Full Side & 1 End)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	52910 lbf (24000 kg)	7330 lbf (3325 kg)	849830 lbf (3780 kN)
22 or 23	G2, U2, 01, 52 (Doors: 2 Full Side & 1 End)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	52910 lbf (24000 kg)	8820 lbf (4000 kg)	848340 lbf (3774 kN)
22 or 23	G2, U2, 01, 52 (Doors: 2 Full Side & 2 End)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	52910 lbf (24000 kg)	8265 lbf (3750 kg)	753650 lbf (3352 kN)
22 or 23	G2, U2, 01, 52 (Doors: 2 Full Side & 0 End)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	52910 lbf (24000 kg)	9170 lbf (4160 kg)	847990 lbf (3772 kN)
22 or 23	H1, 41 (Roof Manhole & Ladder)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	77440 lbf (35125 kg)	13890 lbf (6300 kg)	729430 lbf (3245 kN)
22 or 23	P2,62	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	74960 lbf (34000 kg)	8380 lbf (3800 kg)	?
22 or 23	P3, 63	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	74960 lbf (34000 kg)	6160 lbf (2794 kg)	761920 lbf (3389 kN)
22 or 23	P3, 63	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	88185 lbf (40000 kg)	6725 lbf (3050 kg)	857160 lbf (3813 kN)
22 or 23	P3, 63 (Open End Walls)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	74960 lbf (34000 kg)	6065 lbf (2750 kg)	761920 lbf (3389 kN)
NOTES: <ul style="list-style-type: none"> Stack and Support 20 ft containers on 20 ft containers. Manufacturers of 20 ft containers on This Page: BSL, CIMC, DFIC, SINGAMAS, & SINO-PEAK 							

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Table B.9 Continued

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
22 or 23	P4 or 64	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	74960 lbf (34000 kg)	6395 lbf (2900 kg)	761920 lbf (3389 kN)
22 or 23	P4 or 64	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	66140 lbf (30000 kg)	6150 lbf (2790 kg)	?
22 or 23	R0, R1, 31, 32	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	62700 lbf (30480 kg)	6540 lbf (2968 kg)	809540 lbf (3601 kN)
22 or 23	R0, R1, 31, 32 (Internal Meat Hangers)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	62700 lbf (30480 kg)	8640 lbf (3920 kg)	899500 lbf (4001 kN)
22 or 23	R0, R1, 31, 32 (Recessed Butcher Door)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	52910 lbf (24000 kg)	6440 lbf (2920 kg)	23175 lbf (103 kN)
22 or 23	T0, 70	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	81570 lbf (37000 kg)	8050 lbf (3650 kg)	342865 lbf (1525 kN)
22 or 23	U1, 51 (Removable Hardtop Roof)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	62700 lbf (30480 kg)	6240 lbf (2830 kg)	876640 lbf (3900 kN)
22 or 23	U1, 51 (Soft Roof)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	62700 lbf (30480 kg)	5020 lbf (2277 kg)	899053 lbf (3999 kN)
NOTES: <ul style="list-style-type: none"> Stack and Support 20 ft containers on 20 ft containers. Manufacturers of 20 ft containers on This Page: BSL, CIMC, DFIC, SINGAMAS, & SINO-PEAK 							

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Table B.9 Continued

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
25	B0, 80 (1 Rectangular Discharge End Door)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	71585 lbf (32470 kg)	5445 lbf (2470 kg)	761920 lbf (3389 kN)
25	G0, G1, 00, 10	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	62700 lbf (30480 kg)	5203 lbf (2360 kg)	761920 lbf (3389 kN)
25	G2, U2, 01, 52 (Doors: 1 Full Side & 1 End)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	62700 lbf (30480 kg)	?	761920 lbf (3389 kN)
25	U1, 51 (Soft Roof)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	9 ft- 6 in. (2896 mm)	62700 lbf (30480 kg)	5545 lbf (2515 kg)	761920 lbf (3389 kN)
26	G0, G1, 00, 10	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	18 ft- 6 in. (5639 mm)	31800 lbf (14424 kg)	10670 lbf (4840 kg)	0
28	U0, 50 (No Roof)	19 ft- 10 1/2 in. (6058 mm)	8 ft (2438 mm)	4 ft- 3 in. (1295 mm)	85010 lbf (38560 kg)	4950 lbf (2245 kg)	911575 lbf (4055 kN)

NOTES:

- Stack and Support 20 ft containers on 20 ft containers.
- Manufacturers of 20 ft containers on This Page: BSL, CIMC, SINGAMAS, & SINO-PEAK

Continued

Table B.9 Continued

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAXIMUM COMPRESSIVE FORCE CONTAINER CAN WITHSTAND
2L	G2, U2, 01, 52 (Doors: 1 Full Side & 1 End)	19 ft- 10 1/2 in. (6058 mm)	8 ft- 4 25/64 in. (2550 mm)	8 ft- 6 in. (2591 mm)	71650 lbf (32500 kg)	7230 lbf (3280 kg)	380960 lbf (1695 kN)
2L	G2, U2, 01, 52 (Doors: 2 Full Side & 1 End)	19 ft- 10 1/2 in. (6058 mm)	8 ft- 4 25/64 in. (2550 mm)	8 ft- 6 in. (2591 mm)	71650 lbf (32500 kg)	7230 lbf (3280 kg)	380960 lbf (1695 kN)
2N	B0, 80 (1 Rectangular Discharge End Door)	19 ft- 10 1/2 in. (6058 mm)	8 ft- 2 1/2 in. (2502 mm)	9 ft- 6 in. (2896 mm)	71980 lbf (32650 kg)	6775 lbf (3073 kg)	777400 lbf (3458 kN)
2N	G2, U2, 01, 52 (Doors: 1 Full Side & 0 End)	19 ft- 10 1/2 in. (6058 mm)	8 ft- 2 1/2 in. (2502 mm)	9 ft- 6 in. (2896 mm)	74960 lbf (34000 kg)	7870 lbf (3570 kg)	809540 lbf (3601 kN)
2N	G2, U2, 01, 52 (Doors: 2 Full Side & 0 End)	19 ft- 10 1/2 in. (6058 mm)	8 ft- 2 1/2 in. (2502 mm)	9 ft- 6 in. (2896 mm)	74960 lbf (34000 kg)	8730 lbf (3960 kg)	809540 lbf (3601 kN)

NOTES:

- Stack and Support 20 ft containers on 20 ft containers (Check Widths).
- Manufacturers of 20 ft containers on This Page: CIMC & SINGAMAS

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAX.COMPRESSION FORCE ACTING ON CONTAINER
?2 or ?3	?? (Doors: 2 Full Side & No Ends)	12ft- 2 1/4 in. (3715 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	15560 lbf (7100 kg)	4630 lbf (2100 kg)	56350 lbf (251 kN)

SIZE CODE	TYPE CODE	LENGTH (L)	WIDTH (W)	HEIGHT (H)	MAX. WEIGHT	EMPTY WEIGHT	MAX.COMPRESSION FORCE ACTING ON CONTAINER
12 or 13	G0, G1, 00, 10	9 ft- 11 1/4 in. (2991 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	33600 lbf (15240 kg)	2990 lbf (1356 kg)	72620 lbf (323 kN)
12 or 13	G0, G1, 00, 10	9 ft- 11 1/4 in. (2991 mm)	8 ft (2438 mm)	8 ft- 6 in. (2591 mm)	22400 lbf (10160 kg)	2990 lbf (1356 kg)	201590 lbf (897 kN)

NOTES:

- Stack and Support 12 ft- 2 1/4 in. containers on other 12 ft- 2 1/4 in. containers only (Not an ISO container).
- Stack and Support 9 ft- 11 1/4 in. containers on other 9 ft- 11 1/4 in. containers only (Not an ISO container).
- Manufacturers of 12 ft- 2 1/4 in. and 9 ft- 11 1/4 in. containers: CIMC, SINGAMAS, & SINO-PEAK

Table B.10: 9 ft to 13 ft Shipping Containers.

Shipping Container Manufacturers	
BSL	
CIMC- China International Marine Containers, Ltd.	
CXIC- Changzhou Xinhuchang International Containers Co., Ltd.	
NXIC- Ningbo Xinhuchang International Containers Co., Ltd.	
HXIC- Huizhou Xinhuchang International Containers Co., Ltd.	
CXIC-Wanlong - Jiangsu Wanlong Special Containers Co., Ltd.	
CXIC-Transportation - Changzhou Xinhuchang Int.Containers Co., Ltd	
CXIC-Timber - CXIC Jiashan Timber Products Co., Ltd	
CXIC-Jiutong	
DFIC- Dong Fang International Container Co., Ltd.	
DFICJZ- Dong Fang International Container (JinZhou) Co., Ltd.	
DFICLYG- Dong Fang International Container (LianYungang) Co., Ltd.	
DFICGZ- Dong Fang International Container (Guangzhou) Co., Ltd.	
LYGUSPV- Dong Fang International Container (LYG Chassis) Co., Ltd.	
HUNG DAO	
RYC- Yangzhou Runyang Logistic Equipment Co., Ltd.	
SINGAMAS- Singamas Container Holdings Limited	
SSTC- Foshan Shunde Singamas Tank Container Co., Ltd.	
SSPC- Guangdong Shunde Shun An Da Pacific Container Co., Ltd.	
HPCL- Huizhou Pacific Container Co. Ltd.	
NPCL- Ningbo Pacific Container Co., Ltd.	
QPCL- Qingdao Pacific Container Co., Ltd.	
SBPC- Shanghai Baoshan Pacific Container Co., Ltd.	
SPIC- Shanghai Pacific International Container Co., Ltd.	
SRCC- Shanghai Reeferco Container Co., Ltd.	
SCIC- Singamas Container Industry Co., Ltd.	
TPCC- Tianjin Pacific Container Co. Ltd.	
XPCL- Xiamen Pacific Container Manufacturing Co., Ltd.	
PT Java Pacific Conatiner Factory	
SINO-PEAK- Tianjin Sino-Peak Container Manufacturing Co., Ltd.	

Table B.11: Shipping Container Manufacturers.

APPENDIX C
SHIPPING CONTAINER COMPONENTS

Internationally standard fitting (casting) located at the eight corners of the container structure to provide means of handling, stacking and securing containers. Specifications are defined in ISO 1161.

Dimensions:

178 x 162 x 118 mm

Stress Limits:

$F_y = 40 \text{ ksi } (274.7 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

Figure C.1: ISO Corner Fitting.

An assembly consisting of bottom side rails, cross members, and forklift pockets.

Figure C.2: ISO Shipping Container Base Frame Structure.

Longitudinal structural member situated at the bottom edge of each side of the container and joined to the corner fittings to form a part of the understructure. There are multiple cross sections used as the bottom side rail. The first cross section on the far left is used in the research.

Dimensions:

Length - 5702 mm

Cross Sections - See Below

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

A= 48mm
B= 158 mm
C= 30 mm

A= 48-52 mm
B= 28-30 mm
C= 4.5 mm

A= 30mm, B= 28 mm
C= 4.5 mm,
D=124.5mm
E= 155, F=52 mm

Unknown
Dimensions

Figure C.3: Bottome Side Rail (Base Frame Structure).

Reinforcement plates welded to the bottom side rails and bottom corner fittings, two plates on each side.

Dimensions:

200 x 120-153 x 4.0 mm

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

Figure C.4: Bottome Side Rail Reinforcement Plates (Base Frame Structure).

Lateral structural member attached to the bottom side rails which supports the flooring. Generally there are 18 cross members. Two of the cross members are larger and contain three 4.0 mm gusset support plates. The cross members can be various shapes, but the first two cross sections on the far left are used in this research.

Dimensions:

Length - 2336 mm

Cross Sections - See Below

Spacing between members- Varies from 275- 325 mm

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

A & C= 45 mm
B= 4.0 mm
D=122 mm

A= 75 mm
B= 4.0 mm
C= 45 mm
D= 122 mm

Unknown Dimensions

Figure C.5: Cross Member (Base Frame Structure).

The two, larger cross members are located at the fourth and twelfth cross members from the rear side of the container (door side). Each larger cross member has three 4.0 mm gusset support plates located at the center of the cross member and spaced 550 mm each direction from the center. Each plate fills the cross section.

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

Figure C.6: Cross Member Gusset Plate (Base Frame Structure).

There are two forklift pockets whose centers are 1811 mm from each end of the bottom side rail. ISO requirements should dictate the design of the pockets and reinforcing. This research uses a 2336 x 360 x 3.0 mm top plate and a 200 x 360 x 6.0 mm lower plate. The upper flange and web area above each forklift pocket are reinforced by a 460 x 4.0 mm angle plate.

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

Figure C.7: Forklift Pockets (Base Frame Structure).

The floor covers the entire base frame structure. The flooring is a 28 mm thick, 19 ply hardwood board. The floor is assumed to be fully connected to the base frame structure. The floor is not modeled in this research, and any load acting on the floor is assumed to transfer to the bottom corner fittings. The main focus of this research does not involve modifying the floor or base frame structure.

Figure C.8: ISO Shipping Container Flooring.

The structural assembly at the rear (door end) of the container consisting of the door sill, door header, two corner posts, and four corner fittings which are welded together to make the door-way.

Figure C.9: ISO Shipping Container Rear Frame Structure (Door End).

Lateral structural member at the bottom of the door opening and joined to the corner fittings in the door end frame. The door sill contains four locking cam keepers which are reinforced with four 4.0 mm thick, internal gusset plates. A cut out near each bottom corner fitting is reinforced by a 200 x 75 x 9.0 mm channel section.

Dimensions:

Length - 2340 mm

Cross section – See below

Cam Keeper – See below

Stress Limits:

Door Sill:

$F_y = 50 \text{ ksi (343.3 N/mm}^2\text{)}$

$F_u = 70 \text{ ksi (480.7 N/mm}^2\text{)}$

Cam Keeper:

$F_y = 35 \text{ ksi (245.25 N/mm}^2\text{)}$

$F_u = 60 \text{ ksi (412.0 N/mm}^2\text{)}$

A= 121 mm, B= 162 mm

C= 140.8 mm, D= 65 mm

E= 4.5 mm, F= 45 mm

Varies per manufacturer.
Research physically measured a
cam keeper in a container yard.

Figure C.10: Door Sill (Rear Frame Structure).

There are four 4.0 mm thick gusset plates behind each cam keeper. They are spaced 170 mm and 590 mm from the center of the door sill in each direction. Each gusset plate fills the cross section. There are also two base plates which connect to the corner fittings.

Stress Limits:

$F_y = 50 \text{ ksi (343.3 N/mm}^2\text{)}$

$F_u = 70 \text{ ksi (480.7 N/mm}^2\text{)}$

Figure C.11: Door Gusset Sill Plates (Rear Frame Structure).

Vertical structural member composed of a channel section and pressed steel outer section. There are four cut outs in the outer pressed steel section which are reinforced by small plates.

Dimensions:

Height – 2355 mm

A= 46 mm, B= 280 mm

C= 230 mm, D= 30 mm

E= 6.0 mm, F= 53 mm

G= 12 mm, H= 113 mm

I= 40 mm

Stress Limits:

For outer pressed steel section:

$F_y = 50 \text{ ksi (343.3 N/mm}^2\text{)}$

$F_u = 70 \text{ ksi (480.7 N/mm}^2\text{)}$

For inner channel section:

$F_y = 41 \text{ ksi (284.5 N/mm}^2\text{)}$

$F_u = 71 \text{ ksi (490.5 N/mm}^2\text{)}$

Cut Out varies per manufacturer. This research uses a cut out of 85 x 30 x 53 mm and the reinforcement plates are 10 mm thick.

Figure C.12: Rear Corner Post (Rear Frame Structure).

Lateral structural member situated over the door opening and joined to the corner fittings in the door end frame. The door header contains four locking cam keepers which are reinforced with four 4.0 mm thick, internal gusset plates. There are protection plates and cut outs near the top corner fittings.

Dimensions:

Length - 2340 mm

Cross section – See below

Cam Keeper– See below

Stress Limits:

Door Header:

$F_y = 50 \text{ ksi (343.3 N/mm}^2\text{)}$

$F_u = 70 \text{ ksi (480.7 N/mm}^2\text{)}$

Cam Keeper:

$F_y = 35 \text{ ksi (245.25 N/mm}^2\text{)}$

$F_u = 60 \text{ ksi (412.0 N/mm}^2\text{)}$

A= 83.4 mm, B= 10 mm, C= 3.0 mm, D= 135 mm
E= 4.0 mm, F= 110 mm, G= 110 mm, H= 6.0 mm
I= 3.0 mm, J= 111 mm, K= 161.5 mm, L= 25 mm

Varies per manufacturer.

Figure C.13: Door Header (Rear Frame Structure).

The door header contains four locking cam keepers which are reinforced with four 4.0 mm thick, internal gusset plates. They are spaced 170 mm and 590 mm from the center of the door header in each direction. Each gusset plate fills the cross section.

Dimensions:

97 x 110 x 4.0 mm

Stress Limits:

$F_y = 50 \text{ ksi (343.3 N/mm}^2\text{)}$

$F_u = 70 \text{ ksi (480.7 N/mm}^2\text{)}$

Figure C.14: Door Header Gusset Plates (Rear Frame Structure).

The door header contains two protection plates which are near the top corner fittings.

Dimensions:

330 x 270 x 3.0 mm

with a cut out for the top corner fittings

Stress Limits:

$F_y = 50 \text{ ksi (343.3 N/mm}^2\text{)}$

$F_u = 70 \text{ ksi (480.7 N/mm}^2\text{)}$

Figure C.15: Door Header Protection Plates (Rear Frame Structure).

Each door consists of a steel frame composed of hollow structural steel and channel sections. The steel door frame encloses a corrugated panel. The corrugated panels have five, three, or two corrugations. This research uses the corrugation panel with five corrugations.

Dimensions:

Overall each door – 2254 x 1143 mm

Cross section – See below

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

Door Frame:

Horizontal Members:
150 x 50 x 3.0 mm
channel section

Vertical Members:
100 x 50 x 3.2 mm
rectangular hollow
sections

Door Panel:

5 Corrugations:

Depth: 36 mm
Width: 72 mm
Slope: 68 mm
2.0 mm thick

3 Corrugations:

Depth: 40 mm
Interface: 106 mm
Slope: 22 mm
2.0 mm thick

2 Corrugations:

Unknown

Figure C.16: The Door (Rear Frame Structure).

Both doors have an attached locking assembly which includes locking steel tube bars, anti-racking rings, bearing brackets, bar guide brackets, and cam ends. This research models the Steel Tubes with brackets and locking cams.

Dimensions:

Thickness of tubes - 2.0 mm (assumed)

Thickness of brackets - 3.0mm (assumed)

Physically measured dimensions in container yard

Stress Limits:

Steel Tubes and Brackets:

$F_y = 35 \text{ ksi } (245.25 \text{ N/mm}^2)$

$F_u = 58 \text{ ksi } (402.2 \text{ N/mm}^2)$

Cam Ends:

$F_y = 35 \text{ ksi } (245.25 \text{ N/mm}^2)$

$F_u = 60 \text{ ksi } (412.0 \text{ N/mm}^2)$

Figure C.17: Steel Tube Locking Assembly (Rear Frame Structure).

Four hinges are welded to each door and are attached to the rear corner posts using hinge pins. The research assumes the hinge connection to the rear corner post is welded.

Dimensions:

Physically Measured

Stress Limits:

$F_y = 40 \text{ ksi } (274.7 \text{ N/mm}^2)$

$F_u = 65 \text{ ksi } (451.3 \text{ N/mm}^2)$

Figure C.18: Hinges (Rear Frame Structure).

The roof structure is composed of five corrugated steel panels which are welded together to form one entity located on the upper surface of the container.

Dimensions:

5225 x 2356 x 2.0 mm

Corrugation Shape -

Depth: 20 mm, Pitch: 209 mm

Interface: 91 mm

Slope: 13.5 mm

Outerface: 91 mm

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

Figure C.19: ISO Shipping Container Roof Structure.

Longitudinal structural member situated at the top edge of each side of the container and joined to the corner fittings of the end frames. The top side rail is a square hollow section (Other top side rail sections are a “Z” and “—” shaped, but dimension information is unavailable).

Dimensions:

Length - 2114 mm

Cross Section - 60 x 60 x 3.0 mm

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

Figure C.20: ISO Shipping Container Top Side Rail.

The side wall is a vertically corrugated section composed of multiple welded sheets. There are also small ventilation holes which are excluded from the research.

Dimensions:

5580 x 2329 x 2.0-1.6 mm
(2.0 mm thickness up to 1116 mm from each corner post, then becomes 1.6 mm)

Corrugation Shape -

Outer face: 72 mm, Slope: 68 mm

Inner face: 70 mm, Depth: 36 mm, Pitch: 278 mm

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

Figure C.21: ISO Shipping Container Side Wall.

The front end structure is composed of the front sill and header, two corner posts, four corner fittings, and an end wall welded together.

Figure C.22: ISO Shipping Container Front End Structure.

Lateral structural member situated at the bottom edge of the front end (opposite the door end) of the container and joined to the corner fittings. The front sill contains three 4.0 mm thick, internal gusset plates. A cut out near each bottom corner fitting is reinforced by a 200 x 75 x 9.0 mm channel section.

Dimensions:

Length - 2114 mm

A= 60 mm

B= 49 mm

C= 31 mm

D= 121 mm

E= 4.0mm

F= 45 mm

Stress Limits:

$F_y = 50 \text{ ksi (343.3 N/mm}^2\text{)}$

$F_u = 70 \text{ ksi (480.7 N/mm}^2\text{)}$

Figure C.23: Bottom End Rail/ Front Sill (Front End Structure).

There are three 4.0 mm thick gusset plates located at the center and spaced 520 mm away from the center of the front sill in each direction. Each gusset plate fills the cross section.

Stress Limits:

$F_y = 50 \text{ ksi (343.3 N/mm}^2\text{)}$

$F_u = 70 \text{ ksi (480.7 N/mm}^2\text{)}$

Figure C.24: Front Sill Gusset Plates (Front End Structure).

Vertical structural member composed of a pressed steel section with sill plates attached to bottom corner fitting (dimensions unclear). There are cut outs around the corner fittings.

Dimensions:

Height - 2355 mm

A= 174 mm

B= 50 mm

C= 6.0 mm

D= 40 mm

E= 49 mm

F= 50 mm

G= 159 mm

Stress Limits:

$F_y = 50 \text{ ksi (343.3 N/mm}^2\text{)}$

$F_u = 70 \text{ ksi (480.7 N/mm}^2\text{)}$

Figure C.25: Front Corner Post (Front End Structure).

Lateral structural member situated at the top edge of the front end (opposite the door end) of the container and joined to the corner fittings. There are protection plates near the top corner fittings. There are multiple cross sections for the front header, but the first section is used in this research.

Dimensions:

Length - 2312 mm

Cross sections – See below

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

A = 361 mm

B = 4.0 mm

C = 3.0 mm

D = 60 mm

E = 60 mm

A = 365 mm

B = 4.0 mm

C = 60 mm

D = 87 mm

Figure C.26: Front Header (Front End Structure).

The front header contains two protection plates which are near the top corner fittings.

Dimensions:

274 x 270 x 3.0 mm

with a cut out for the

top corner fittings

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$

$F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

Figure C.27: Front Header Protection Plate (Front End Structure).

The front wall is a vertically corrugated section composed of multiple welded sheets.

Dimensions:

2331 x 2038 x 1.6 – 2.0 mm
(Thickness varies from manufacturer,
research uses 2.0 mm)

Corrugation Shape -

Outer face: 110 mm, Depth 45.6 mm
Inner face: 104 mm, Slope: 18 mm

Stress Limits:

$F_y = 50 \text{ ksi } (343.3 \text{ N/mm}^2)$
 $F_u = 70 \text{ ksi } (480.7 \text{ N/mm}^2)$

Figure C.28: Front Wall (Front End Structure).

APPENDIX D

SHIPPING CONTAINER COMPUTER MODELS

	Corner Fitting		Bottom Side Rail (<i>Base Frame Structure</i>)		
	Profile	Mesh (Each Corner Fitting)	Profile		Mesh (Each Side Rail)
Actual Container	Figure C.1 See ISO 1161 178 x 162 x 118 mm	NA		Dimensions: Figure C.3 $A = 1.58 \text{ in}^2 (1021.5 \text{ mm}^2)$ $I_{xx} = 7.89 \text{ in}^4 (3.3\text{E}6 \text{ mm}^4)$ $I_{yy} = 0.3 \text{ in}^4 (3.7\text{E}5 \text{ mm}^4)$	NA
Model 1	Does not contain Corner Fittings	NA		Same as Figure C.3 (<i>Excludes</i> : Forklift Pockets/Reinforcing, & Reinforcement Plates)	243 Nodes 242 Elements (B31- Linear Line Elem.)
Model 2	Does not contain Corner Fittings	NA		Same as Figure C.3 (<i>Excludes</i> : Forklift Pockets/Reinforcing, & Reinforcement Plates)	243 Nodes 242 Elements (B31- Linear Line Elem.)
Model 3	Same as actual container (<i>Excludes</i> : Most Fillets)	2560 Nodes 8056 Elements (C3D4- Linear Tetrahedral Elem.)		Same as Figure C.3 (<i>Excludes</i> : Forklift Pockets/Reinforcing, & Reinforcement Plates)	229 Nodes 228 Elements (B31- Linear Line Elem.)
Model 4	Same as actual container (<i>Excludes</i> : Most Fillets)	2560 Nodes 8056 Elements (C3D4- Linear Tetrahedral Elem.)		Same as Figure C.3 (<i>Excludes</i> : Forklift Pockets/Reinforcing, & Reinforcement Plates)	13886 Nodes 39115 Elements (C3D4- Linear Tetrahedral Elements)
Model 5	Same as actual container (<i>Excludes</i> : Most Fillets)	2560 Nodes 8056 Elements (C3D4- Linear Tetrahedral Elem.)		Same as Figure C.3 (<i>Excludes</i> : Forklift Pockets/Reinforcing, & Reinforcement Plates)	13886 Nodes 39115 Elements (C3D4- Linear Tetrahedral Elements)

Continued

Table D.1: Container Component Dimensions and Mesh Information for Each Container Model.

Table D.1 Continued

	Cross Members (<i>Base Frame Structure</i>)		Door Sill (<i>Rear Frame Structure</i>)	
	Profile (Each Cross Member)	Mesh (Each Cross Member)	Profile	Mesh
Actual Container	Dimensions: Figure C.5 $A = 1.26\text{--}1.45\text{ in}^2$ (815-936 mm ²) $I_{xx} = 4.19\text{ in}^4$ (1.7E6 mm ⁴) $I_{yy} = 0.35\text{ in}^4$ (1.5E5 mm ⁴)	NA	Dimensions: Figure C.10 $A = 2.74\text{ in}^2$ (1770 mm ²) $I_{xx} = 19.46\text{ in}^4$ (8.0E6 mm ⁴) $I_{yy} = 6.11\text{ in}^4$ (2.5E6 mm ⁴)	NA
Model 1	Same as Figure C.5 (<i>Excludes: Gusset Plates</i>)	79 Nodes 78 Elements (B31- Linear Line Elem.)	186 x 89 x 3.3 mm $A = 2.75\text{ in}^2$ (1771 mm ²) $I_{xx} = 19.41\text{ in}^4$ (8.0E6 mm ⁴) $I_{yy} = 6.16\text{ in}^4$ (2.5E6 mm ⁴)	99 Nodes 98 Elements (B31- Linear Line Elem.)
Model 2	Same as Figure C.5 (<i>Excludes: Gusset Plates</i>)	79 Nodes 78 Elements (B31- Linear Line Elem.)	Same as Figure C.10 (<i>Excludes: Gusset Plates, cam keepers, Channel Cut Outs, & Corner Cut Outs</i>)	99 Nodes 98 Elements (B31- Linear Line Elem.)
Model 3	Same as Figure C.5 (<i>Excludes: Gusset Plates</i>)	79 Nodes 78 Elements (B31- Linear Line Elem.)	Same as Figure C.10 (<i>Excludes: Gusset Plates, cam keepers, Channel Cut Outs, & Corner Cut Outs</i>)	86 Nodes 85 Elements (B31- Linear Line Elem.)
Model 4	Same as Figure C.5 (<i>Excludes: Gusset Plates</i>)	79 Nodes 78 Elements (B31- Linear Line Elem.)	Same as Figure C.10	21922 Nodes 64544 Elements (C3D4- Linear Tetrahedral Elem.)
Model 5	Same as Figure C.5 (<i>Excludes: Gusset Plates</i>)	79 Nodes 78 Elements (B31- Linear Line Elem.)	Same as Figure C.10	21922 Nodes 64544 Elements (C3D4- Linear Tetrahedral Elem.)

Continued

Table D.1 Continued

	Rear Corner Post (<i>Rear Frame Structure</i>)		Door Header (<i>Rear Frame Structure</i>)	
	Profile	Mesh (Each Corner Post)	Profile	Mesh
Actual Container	Dimensions: Figure C.12 $A = 6.08 \text{ in}^2 (3924 \text{ mm}^2)$ $I_{xx} = 46.3 \text{ in}^4 (19.2\text{E}6 \text{ mm}^4)$ $I_{yy} = 2.7 \text{ in}^4 (1.1\text{E}6 \text{ mm}^4)$	NA	Dimensions: Figure C.13 $A = 5.32 \text{ in}^2 (3433 \text{ mm}^2)$ $I_{xx} = 15.9 \text{ in}^4 (6.6\text{E}6 \text{ mm}^4)$ $I_{yy} = 85.4 \text{ in}^4 (3.6\text{E}7 \text{ mm}^4)$	NA
Model 1	222 x 43 x 7.9 mm $A = 6.1 \text{ in}^2 (3937 \text{ mm}^2)$ $I_{xx} = 46.45 \text{ in}^4 (19.3\text{E}6 \text{ mm}^4)$ $I_{yy} = 2.7 \text{ in}^4 (1.1\text{E}6 \text{ mm}^4)$	105 Nodes 104 Elements (B31- Linear Line Elem.)	134 x 109 x 3.7 mm $A = 2.7 \text{ in}^2 (1743 \text{ mm}^2)$ $I_{xx} = 11.23 \text{ in}^4 (4.7\text{E}6 \text{ mm}^4)$ $I_{yy} = 8.16 \text{ in}^4 (3.4\text{E}6 \text{ mm}^4)$	99 Nodes 98 Elements (B31- Linear Line Elem.)
Model 2	222 x 43 x 7.9 mm $A = 6.1 \text{ in}^2 (3937 \text{ mm}^2)$ $I_{xx} = 46.45 \text{ in}^4 (19.3\text{E}6 \text{ mm}^4)$ $I_{yy} = 2.7 \text{ in}^4 (1.1\text{E}6 \text{ mm}^4)$	105 Nodes 104 Elements (B31- Linear Line Elem.)	Same as Figure C.13 (Excludes: Protection & Gusset Plates, Cam Keepers, & Corner Cut Outs)	99 Nodes 98 Elements (B31- Linear Line Elem.)
Model 3	222 x 43 x 7.9 mm $A = 6.1 \text{ in}^2 (3937 \text{ mm}^2)$ $I_{xx} = 46.45 \text{ in}^4 (19.3\text{E}6 \text{ mm}^4)$ $I_{yy} = 2.7 \text{ in}^4 (1.1\text{E}6 \text{ mm}^4)$	95 Nodes 94 Elements (B31- Linear Line Elem.)	Same as Figure C.13 (Excludes: Protection & Gusset Plates, Cam Keepers, & Corner Cut Outs)	86 Nodes 85 Elements (B31- Linear Line Elem.)
Model 4	Same as Figure C.12 (Excludes: Cut Outs and Reinforcement Plates)	18303 Nodes 52364 Elements (C3D4- Linear Tetrahedral Elem.)	Same as Figure C.13 (Excludes: Cam Keepers)	39080 Nodes 116602 Elements (C3D4- Linear Tetrahedral Elem.)
Model 5	Same as Figure C.12 (Excludes: Cut Outs and Reinforcement Plates)	18303 Nodes 52364 Elements (C3D4- Linear Tetrahedral Elem.)	Same as Figure C.13 (Excludes: Cam Keepers)	39080 Nodes 116602 Elements (C3D4- Linear Tetrahedral Elem.)

Continued

Table D.1 Continued

	The Doors (<i>Rear Frame Structure</i>)		Roof (<i>Roof Structure</i>)	
	Profile	Mesh	Profile	Mesh
Actual Container	See Figures C.16, C.17, and C.18	NA	Dimensions: Figure C.19 $A = 17.6 \text{ in}^2 (11350 \text{ mm}^2)$ $I_{xx} = 1.93 \text{ in}^4 (8.0\text{E}5 \text{ mm}^4)$ $I_{yy} = 62035 \text{ in}^4 (2.6\text{E}10 \text{ mm}^4)$	NA
Model 1	$2438 \times 1.49 \text{ mm}$ $A = 5.6 \text{ in}^2 (3632 \text{ mm}^2)$ $I_{xx} = 0.0016 \text{ in}^4 (672 \text{ mm}^4)$ $I_{yy} = 4323 \text{ in}^4 (1.8\text{E}9 \text{ mm}^4)$	<i>Uniform Mesh</i> 7134 Nodes 6966 Elements (S4R- Linear Quad. Elem.)	$6058 \times 1.4 \text{ mm}$ $A = 13.2 \text{ in}^2 (8481 \text{ mm}^2)$ $I_{xx} = 0.0033 \text{ in}^4 (1385 \text{ mm}^4)$ $I_{yy} = 62316 \text{ in}^4 (2.6\text{E}10 \text{ mm}^4)$	<i>Uniform Mesh</i> 16646 Nodes 16362 Elements (S4R- Linear Quad. Elem.)
Model 2	$2438 \times 1.49 \text{ mm}$ $A = 5.6 \text{ in}^2 (3632 \text{ mm}^2)$ $I_{xx} = 0.0016 \text{ in}^4 (672 \text{ mm}^4)$ $I_{yy} = 4323 \text{ in}^4 (1.8\text{E}9 \text{ mm}^4)$	<i>Uniform Mesh</i> 7134 Nodes 6966 Elements (S4R- Linear Quad. Elem.)	$6058 \times 1.4 \text{ mm}$ $A = 13.2 \text{ in}^2 (8481 \text{ mm}^2)$ $I_{xx} = 0.0033 \text{ in}^4 (1385 \text{ mm}^4)$ $I_{yy} = 62316 \text{ in}^4 (2.6\text{E}10 \text{ mm}^4)$	<i>Uniform Mesh</i> 16646 Nodes 16362 Elements (S4R- Linear Quad. Elem.)
Model 3	$2276 \times 1.8 \text{ mm}$ $A = 6.35 \text{ in}^2 (4096 \text{ mm}^2)$ $I_{xx} = 0.0027 \text{ in}^4 (1106 \text{ mm}^4)$ $I_{yy} = 4249 \text{ in}^4 (1.7\text{E}9 \text{ mm}^4)$ <i>(Includes: Corner Cut Outs)</i>	7447 Nodes 7235 Elements (S4- Linear Quad. Elm.) 67 Elements (S3- Linear Tri. Elm.)	$5880 \times 1.6 \text{ mm}$ $A = 14.58 \text{ in}^2 (9408 \text{ mm}^2)$ $I_{xx} = 0.0048 \text{ in}^4 (2007 \text{ mm}^4)$ $I_{yy} = 65123 \text{ in}^4 (2.7\text{E}10 \text{ mm}^4)$ <i>(Includes: Corner Cut Outs)</i>	15471 Nodes 15132 Elements (S4-Lin.Quad El) 98 Elements (S3-Lin.Tri.Elm.)
Model 4	Front Wall Substitution $2340 \times 2.0 \text{ mm}$ $A = 9.06 \text{ in}^2 (5847 \text{ mm}^2)$ $I_{xx} = 5.22 \text{ in}^4 (2.1\text{E}6 \text{ mm}^4)$ $I_{yy} = 6546.22 \text{ in}^4 (2.7\text{E}9 \text{ mm}^4)$	8259 Nodes 8076 Elements (S4- Linear Quadrilateral Elements)	Same as Figure C.19	32727 Nodes 32013 Elements (S4-Lin.Quad El) 668 Elements (S3-Lin.Tri.Elm.)
Model 5	Front Wall Substitution $2340 \times 2.0 \text{ mm}$ $A = 9.06 \text{ in}^2 (5847 \text{ mm}^2)$ $I_{xx} = 5.22 \text{ in}^4 (2.1\text{E}6 \text{ mm}^4)$ $I_{yy} = 6546.22 \text{ in}^4 (2.7\text{E}9 \text{ mm}^4)$	69786 Nodes 69244 Elements (S4- Linear Quad. Elm.) 20 Elements (S3- Linear Tri. Elm.)	Same as Figure C.19	131125 Nodes 129799 Elements (S4- Lin.Quad.Elm.) 1269 Elements (S3- Linear Triangular .Elm.)

Continued

Table D.1 Continued

	Top Side Rail		Side Wall	
	Profile	Mesh	Profile	Mesh (Each Side Wall)
Actual Container	<p>Dimensions: Figure C.20 $A = 1.06 \text{ in}^2 (684 \text{ mm}^2)$ $I_{xx} = 0.89 \text{ in}^4 (3.7\text{E}5 \text{ mm}^4)$ $I_{yy} = 0.89 \text{ in}^4 (3.7\text{E}5 \text{ mm}^4)$</p>	NA	<p>Dimensions: Figure C.21 $A = 16.08 \text{ in}^2 (10373 \text{ mm}^2)$ $I_{xx} = 4.73 \text{ in}^4 (1.9\text{E}6 \text{ mm}^4)$ $I_{yy} = 70306 \text{ in}^4 (2.9\text{E}10 \text{ mm}^4)$</p>	NA
Model 1	<p>Same as Figure C.20</p>	243 Nodes 242 Elements (B31- Linear Line Elem.)	<p>6058 x 1.65 mm $A = 15.5 \text{ in}^2 (9996 \text{ mm}^2)$ $I_{xx} = 0.0054 \text{ in}^4 (2268 \text{ mm}^4)$ $I_{yy} = 73443 \text{ in}^4 (3.0\text{E}10 \text{ mm}^4)$ <i>(Excludes: Ventilation Holes)</i></p>	<i>Uniform Mesh</i> 17661 Nodes 17473 Elements (S4R- Linear Quad. Elem.)
Model 2	<p>Same as Figure C.20</p>	243 Nodes 242 Elements (B31- Linear Line Elem.)	<p>6058 x 1.65 mm $A = 15.5 \text{ in}^2 (9996 \text{ mm}^2)$ $I_{xx} = 0.0054 \text{ in}^4 (2268 \text{ mm}^4)$ $I_{yy} = 73443 \text{ in}^4 (3.0\text{E}10 \text{ mm}^4)$ <i>(Excludes: Ventilation Holes)</i></p>	<i>Uniform Mesh</i> 17661 Nodes 17473 Elements (S4R- Linear Quad. Elem.)
Model 3	<p>Same as Figure C.20</p>	229 Nodes 228 Elements (B31- Linear Line Elem.)	<p>5880 x 1.81 mm $A = 16.5 \text{ in}^2 (10643 \text{ mm}^2)$ $I_{xx} = 0.0070 \text{ in}^4 (2905 \text{ mm}^4)$ $I_{yy} = 73670 \text{ in}^4 (3.0\text{E}10 \text{ mm}^4)$ <i>(Excludes: Ventilation Holes)</i> <i>(Includes: Corner Cut Outs)</i></p>	16510 Nodes 16243 Elements (S4- Lin. Quad. Elm.) 60 Elements (S3- Line. Tri. Elm.)
Model 4	<p>Same as Figure C.20</p>	25144 Nodes 75300 Elements (C3D4- Linear Tetrahedral Elem.)	<p>Same as Figure C.21 <i>(Excludes: Ventilation Holes)</i></p>	16195 Nodes 15912 Elements (S4- Linear Quad. Elements)
Model 5	<p>Same as Figure C.20</p>	25144 Nodes 75300 Elements (C3D4- Linear Tetrahedral Elem.)	<p>Same as Figure C.21 <i>(Excludes: Ventilation Holes)</i></p>	140868 Nodes 140033 Elements (S4- Linear Quad. Elements)

Continued

Table D.1 Continued

	Bottom End Rail/ Front Sill (<i>Front End Structure</i>)		Front Corner Post (<i>Front End Structure</i>)	
	Profile	Mesh	Profile	Mesh (Each Corner Post)
Actual Container	<p>Dimensions: Figure C.23 $A = 2.02 \text{ in}^2$ (1300 mm²) $I_{xx} = 9.52 \text{ in}^4$ (3.9E6 mm⁴) $I_{yy} = 2.31 \text{ in}^4$ (9.6E5 mm⁴)</p>	NA	<p>Dimensions: Figure C.25 $A = 4.8 \text{ in}^2$ (3096 mm²) $I_{xx} = 20.5 \text{ in}^4$ (8.5E6 mm⁴) $I_{yy} = 48.1 \text{ in}^4$ (20.0E6 mm⁴)</p>	NA
Model 1	<p>156 x 64 x 3.0 mm $A = 1.99 \text{ in}^2$ (1284 mm²) $I_{xx} = 9.45 \text{ in}^4$ (3.9E6 mm⁴) $I_{yy} = 2.33 \text{ in}^4$ (9.6E5 mm⁴)</p>	99 Nodes 98 Elements (B31- Linear Line Elem.)	<p>218 x 126 x 4.6 mm $A = 4.77 \text{ in}^2$ (3080 mm²) $I_{xx} = 20.7 \text{ in}^4$ (8.6E6 mm⁴) $I_{yy} = 48.48 \text{ in}^4$ (20.1E6 mm⁴)</p>	105 Nodes 104 Elements (B31- Linear Line Elem.)
Model 2	<p>Same as actual container (<i>Excludes:</i> Gusset Plates & Channel Cut Outs)</p>	99 Nodes 98 Elements (B31- Linear Line Elem.)	<p>Same as Figure C.25 (<i>Excludes:</i> Corner Cut Outs and Sill Plates)</p>	105 Nodes 104 Elements (B31- Linear Line Elem.)
Model 3	<p>Same as Figure C.23 (<i>Excludes:</i> Gusset Plates & Channel Cut Outs)</p>	86 Nodes 85 Elements (B31- Linear Line Elem.)	<p>218 x 126 x 4.6 mm $A = 4.77 \text{ in}^2$ (3080 mm²) $I_{xx} = 20.7 \text{ in}^4$ (8.6E6 mm⁴) $I_{yy} = 48.48 \text{ in}^4$ (20.1E6 mm⁴)</p>	95 Nodes 94 Elements (B31- Linear Line Elem.)
Model 4	<p>Same as Figure C.23</p>	15377 Nodes 44858 Elements (C3D4- Linear Tetrahedral Elem.)	<p>Same as Figure C.25</p>	25349 Nodes 74382 Elements (C3D4- Linear Tetra. Elem.)
Model 5	<p>Same as Figure C.23</p>	15377 Nodes 44858 Elements (C3D4- Linear Tetrahedral Elem.)	<p>Same as Figure C.25</p>	25349 Nodes 74382 Elements (C3D4- Linear Tetra. Elem.)

Continued

Table D.1 Continued

	Front Header (<i>Front End Structure</i>)		Front Wall (<i>Front End Structure</i>)	
	Profile	Mesh	Profile	Mesh
Actual Container	<p>Dimensions: Figure C.26 $A = 3.3 \text{ in}^2 (2128 \text{ mm}^2)$ $I_{xx} = 1.27 \text{ in}^4 (5.3\text{E}5 \text{ mm}^4)$ $I_{yy} = 88.5 \text{ in}^4 (3.7\text{E}7 \text{ mm}^4)$</p>	NA	<p>Dimensions: Figure C.28 $A = 7.76 \text{ in}^2 (5009 \text{ mm}^2)$ $I_{xx} = 4.58 \text{ in}^4 (1.9\text{E}6 \text{ mm}^4)$ $I_{yy} = 4134 \text{ in}^4 (1.7\text{E}9 \text{ mm}^4)$</p>	NA
Model 1	<p>60 x 60 x 3.0 mm $A = 1.06 \text{ in}^2 (684 \text{ mm}^2)$ $I_{xx} = 0.89 \text{ in}^4 (3.7\text{E}5 \text{ mm}^4)$ $I_{yy} = 0.89 \text{ in}^4 (3.7\text{E}5 \text{ mm}^4)$</p>	99 Nodes 98 Elements (B31- Linear Line Elem.)	<p>2438 x 1.49 mm $A = 5.6 \text{ in}^2 (3632 \text{ mm}^2)$ $I_{xx} = 0.0016 \text{ in}^4 (672 \text{ mm}^4)$ $I_{yy} = 4323 \text{ in}^4 (1.8\text{E}9 \text{ mm}^4)$</p>	<i>Uniform Mesh</i> 7134 Nodes 6966 Elements (S4R- Linear Quad. Elem.)
Model 2	<p>Same as Figure C.26 (<i>Excludes:</i> Protection Plates & Corner Cut Outs)</p>	99 Nodes 98 Elements (B31- Linear Line Elem.)	<p>2438 x 1.49 mm $A = 5.6 \text{ in}^2 (3632 \text{ mm}^2)$ $I_{xx} = 0.0016 \text{ in}^4 (672 \text{ mm}^4)$ $I_{yy} = 4323 \text{ in}^4 (1.8\text{E}9 \text{ mm}^4)$</p>	<i>Uniform Mesh</i> 7134 Nodes 6966 Elements (S4R- Linear Quad. Elem.)
Model 3	<p>Same as Figure C.26 (<i>Excludes:</i> Protection Plates & Corner Cut Outs)</p>	86 Nodes 85 Elements (B31- Linear Line Elem.)	<p>2276 x 1.8 mm $A = 6.35 \text{ in}^2 (4096 \text{ mm}^2)$ $I_{xx} = 0.0027 \text{ in}^4 (1106 \text{ mm}^4)$ $I_{yy} = 4249 \text{ in}^4 (1.7\text{E}9 \text{ mm}^4)$ (<i>Includes:</i> Corner Cut Outs)</p>	7447 Nodes 7235 Elements (S4- Lin. Quad. Elm.) 67 Elements (S3- Lin.Tri. Elm.)
Model 4	<p>Same as Figure C.26</p>	28899 Nodes 86150 Elements (C3D4- Linear Tetra. Elem.)	<p>Same as Figure C.28</p>	8259 Nodes 8076 Elements (S4- Linear Quad. Elements)
Model 5	<p>Same as Figure C.26</p>	28899 Nodes 86150 Elements (C3D4- Linear Tetra. Elem.)	<p>Same as Figure C.28</p>	60840 Nodes 60347 Elements (S4- Linear Quad. Elements)

	Roof		Side Walls	Front/Rear Walls	Corner Fittings		Front Corner Posts

Elements Failing Quality Check (% total for component)	Warpage	(0%)	None	None	Tet Collapse	(0%)	Aspect	(0%)
	Chord Dev	(0%)			Vol skew	(0%)	Tet Collapse	(0%)
	Jacobian	(0%)					Vol skew	(0%)
							Vol AR	(0%)
Hypermesh (2009) Meshing Information	2D Automesh		2D Automesh	2D Automesh	3D Tetramesh		3D Tetramesh	
	Size and Bias		Size and Bias	Size and Bias	2D: Trias, 3D: Tetras		2D: Trias, 3D: Tetras	
	Element Size= 10		Element Size= 20	Element Size= 20	Element Size=5		Element Size=5	
	Mesh Type: Mixed		Mesh Type: Mixed	Mesh Type: Mixed	Optimize Mesh Quality		Optimize Mesh Quality	
ABAQUS/CAE (2010) Information	Total Number of Nodes:131125		Total Number of Nodes: 75114	Total Number of Nodes: 29328	Total No. of Nodes: 114018		Total No. of Nodes: 215283	
	Total Number of Elements: 129799 (S4) 1269 (S3)		Total Number of Elements: 74270 (S4)	Total Number of Elements: 28845 (S4)	Total Number of Elements: 448536 (C3D4)		Total Number of Elements: 648819 (C3D4)	
	Warnings: 17 Distorted Isoparametric Elm. & 8 Warped Elem. (nodes not adjusted)		Warnings: None	Warnings: None	Warnings: None		Warnings: None	

Continued

Table D.2: Meshing Information for Final Container Model.

Table D.2 Continued

	Front Header		Front Sill		Base Side Rail	Side Top Rails		Rear Corner Posts

Elements Failing Quality Check (% total for component)	Tet Collapse	(0%)	Tet Collapse	(0%)	None	Vol skew	(0%)	Tet Collapse	(0%)
	Vol skew	(0%)	Vol skew	(0%)				Vol skew	(0%)
Hypermesh (2009) Meshing Information	3D Tetramesh		3D Tetramesh		3D Tetramesh	3D Tetramesh		3D Tetramesh	
	2D: Trias, 3D: Tetras		2D: Trias, 3D: Tetras		2D: Trias, 3D: Tetras	2D: Trias, 3D: Tetras		2D: Trias, 3D: Tetras	
	Element Size=8		Element Size=8		Element Size=8	Element Size=8		Element Size=5	
	Optimize Mesh Quality		Optimize Mesh Quality		Optimize Mesh Quality	Optimize Mesh Quality		Optimize Mesh Quality	
ABAQUS/CAE (2010) Information	Total Number of Nodes: 45437		Total Number of Nodes: 24268		Total Number of Nodes: 84304	Total Number of Nodes: 85760		Total Number of Nodes: 233734	
	Total Number of Elements: 135542 (C3D4)		Total Number of Elements: 71243 (C3D4)		Total Number of Elements: 244002 (C3D4)	Total Number of Elements: 256920 (C3D4)		Total Number of Elements: 751731 (C3D4)	
	Warnings: 2 Distorted Tetrahedral Elements (nodes not adjusted)		Warnings: None		Warnings: None	Warnings: None		Warnings: None	

Continued

Table D.2 Continued

	Door Header		Door Sill		Base Beam Plate		Cross Members

Elements Failing Quality Check (% total for component)	Aspect	(0%)	Tet Collapse	(0%)	Vol skew	(0%)	None
	Tet Collapse	(0%)	Vol skew	(0%)			
	Vol skew	(0%)					
	Vol AR	(0%)					
	Min Angle	(0%)					
Hypermesh (2009) Meshing Information	3D Tetramesh		3D Tetramesh		3D Tetramesh		Meshed in Abaqus/CAE (2010) Element Size=8
	2D: Trias, 3D: Tetras		2D: Trias, 3D: Tetras		2D: Trias, 3D: Tetras		
	Element Size=5		Element Size=8		Element Size=5		
	Optimize Mesh Quality		Optimize Mesh Quality		Optimize Mesh Quality		
ABAQUS/CAE (2010) Information	Total Number of Nodes: 158528		Total Number of Nodes: 34696		Total Number of Nodes: 11405		Total Number of Nodes: 5274
	Total Number of Elements: 487397 (C3D4)		Total Number of Elements: 102648 (C3D4)		Total Number of Elements: 32443 (C3D4)		Total Number of Elements: 5256 (B31)
	Warnings: 11 Distorted Tetrahedral Elements (nodes not adjusted)		Warnings: 1 Distorted Tetrahedral Elements (nodes not adjusted)		Warnings: None		Warnings: None

Loading Scenario 1	M1	M4	M6	M2	M3	M7	M5	M8

Maximum Applied Force (Each Corner Fitting)	942 kN (211.7 kip)	942 kN (211.7 kip)	942 kN (211.7 kip)	942 kN (211.7 kip)	735 kN (165 kip)	735 kN (165 kip)	725.2 kN (163 kip)	717.3 kN (161 kip)
Maximum Applied Force % Change from M1	---	0%	0%	0%	-22%	-22%	-23%	-24%
Displacement	1.25 mm (0.05 in.)	1.25 mm (0.05 in.)	2.2 mm (0.087 in.)	7.64 mm (0.3 in.)	7.8 mm (0.3 in.)	7.8 mm (0.3 in.)	9.8 mm (0.38 in.)	9.8 mm (0.38 in.)
Stiffness	754 kN/mm (4303 kip/in.)	754 kN/mm (4303 kip/in.)	428 kN/mm (2445 kip/in.)	124 kN/mm (707 kip/in.)	94 kN/mm (538 kip/in.)	94 kN/mm (538 kip/in.)	74 kN/mm (423 kip/in.)	73 kN/mm (418 kip/in.)
Stiffness % Change from M1	---	0%	-43%	-84%	-87%	-87%	-90%	-90%
Simulation Time (seconds)	4613	2829	4043	2797	4219	4467	2622	1857

Continued

Table D.3: Container Model Results for Loading Scenario 1.

Table D.3 Continued

Loading Scenario 1	Original Container (M1)	Sidewalls Removed (M2)	Endwalls Removed (M3)	Roof Removed (M4)

Container Stress <i>Exaggerated Deflection</i>
Yielding Location
	Bottom Face of Door Header by Corner Fittings (Rear Wall Removed for Clarity)	Bottom Face of Door Header by Corner Fittings (Rear Wall Removed for Clarity)	Door Header connection to Rear Corner Posts	Bottom Face of Door Header by Corner Fittings (Rear Wall Removed for Clarity)

Continued

Table D.3 Continued

Loading Scenario 1	Walls Removed (M5)	Single Sidewall Removed (M6)	Rear Wall Removed (M7)	Walls & Roof Removed (M8)

Container Stress <i>Exaggerated Deflection</i>
Yielding Location
	Door Header connection to Rear Corner Posts	Bottom Face of Door Header by Corner Fittings (Rear Wall Removed for Clarity)	Door Header connection to Rear Corner Posts	Door Header connection to Rear Corner Posts

Continued

Table D.3 Continued

Loading Scenario 1		Maximum Applied Force & Displacement at Yielding	Deformed Shape of Container (Exaggerated Displacement with walls and roof removed)	Yielding Location (Circled in Red)
M1		942 kN (211.7 kip) 1.25 – 7.64 mm (0.05 – 0.3 in.)		Bottom Face of Door Header
M4
M6
M2
M3		735 kN (165 kip) 7.8 mm (0.3 in.)		Door Header at Rear Corner Posts
M7
M5		717.3 - 725.2 kN (161 – 163 kip) 9.8 mm (0.38 in.)		Door Header at Rear Corner Posts
M8

Loading Scenario 2	M3	M8	M5	M2	M6	M1	M4	M7

Maximum Applied Force (Each Corner Fitting)	1046 kN (235 kip)	1044 kN (234.7 kip)	1044 kN (234.7 kip)	1015 kN (228 kip)	942 kN (212 kip)	942 kN (211.7 kip)	942 kN (211.7 kip)	654 kN (147 kip)
Maximum Applied Force % Change from M1	+11%	+11%	+11%	+8%	0%	---	0%	-31%
Displacement	2.76 mm (0.11 in.)	5.3 mm (0.21 in.)	5.33 mm (0.21 in.)	4.88 mm (0.19 in.)	2.60 mm (0.10 in.)	1.38 mm (0.05 in.)	1.38 mm (0.05 in.)	7.82 mm (0.31 in.)
Stiffness	379 kN/mm (2164 kip/in.)	197 kN/mm (1125 kip/in.)	196 kN/mm (1118 kip/in.)	208 kN/mm (1188 kip/in.)	362 kN/mm (2068 kip/in.)	683 kN/mm (3898 kip/in.)	683 kN/mm (3898 kip/in.)	84 kN/mm (478 kip/in.)
Stiffness % Change from M1	-44%	-71%	-71%	-70%	-47%	---	-0%	-88%
Simulation Time (seconds)	4202	1945	2755	3240	4068	4675	2882	4431

Continued

Table D.4: Container Model Results for Loading Scenario 2.

Table D.4 Continued

Loading Scenario 2	Original Container (M1)	Sidewalls Removed (M2)	Endwalls Removed (M3)	Roof Removed (M4)

Container Stress <i>Exaggerated Deflection</i>
Yielding Location
	Front Corner Posts at Connection to Top Corner Fittings	Front Corner Posts at Connection to Top Corner Fittings	Front Corner Posts at Connection to Top Corner Fittings	Front Corner Posts at Connection to Top Corner Fittings

Continued

Table D.4 Continued

Loading Scenario 2	Walls Removed (M5)	Single Sidewall Removed (M6)	Rear Wall Removed (M7)	Walls & Roof Removed (M8)

<div>Container Stress</div> <div>Exaggerated Deflection</div>
<div>Yielding Location</div>
	Front Corner Posts at Connection to Top Corner Fittings	Front Corner Posts at Connection to Top Corner Fittings	Door Header connection to Rear Corner Posts	Front Corner Posts at Connection to Top Corner Fittings

Continued

Table D.4 Continued

Loading Scenario 2		Maximum Applied Force & Displacement at Yielding	Deformed Shape of Container (Exaggerated Displacement with walls and roof removed)	Yielding Location (Circled in Red)	
M3		1015 - 1046 kN (228 - 235 kip) 2.76 – 5.3 mm (0.11 – 0.21 in.)		Front Corner Posts at Connection to Top Corner Fittings (inside container)	
M8			M3 only		
M5
M2
M6		942 kN (211.7 kip) 1.38 – 2.6 mm (0.05 – 0.1 in.)		Front Corner Posts at Connection to Top Corner Fittings (inside container)	
M1			M6 only		
M4
M7		Applied at Rear of Container 654 kN (147 kip) 7.82 mm (0.31 in.)		Door Header at Rear Corner Posts	

Loading Scenario 3	M5	M8	M3	M7	M6	M2	M1	M4

Maximum Applied Force (Each Corner Fitting)	1180 kN (265 kip)	1117 kN (251 kip)	1073 kN (241 kip)	996 kN (224 kip)	977.7 kN (220 kip)	943.2 kN (212 kip)	942 kN (211.7 kip)	942 kN (211.7 kip)
Maximum Applied Force % Change from M1	+25%	+19%	+14%	+6%	+4%	0%	---	0%
Displacement	11.18 mm (0.44 in.)	11.3 mm (0.44 in.)	6.55 mm (0.26 in.)	5.6 mm (0.22 in.)	2.36 mm (0.09 in.)	4.54 mm (0.18 in.)	1.38 mm (0.05 in.)	1.41 mm (0.06 in.)
Stiffness	106 kN/mm (603 kip/in.)	99 kN/mm (564 kip/in.)	164 kN/mm (935 kip/in.)	178 kN/mm (1015 kip/in.)	414 kN/mm (2365 kip/in.)	208 kN/mm (1186 kip/in.)	683 kN/mm (3898 kip/in.)	668 kN/mm (3815 kip/in.)
Stiffness % Change from M1	-85%	-86%	-76%	-74%	-39%	-70%	---	-2%
Simulation Time (seconds)	4017	3650	4001	2870	2777	3488	3850	1881

Continued

Table D.5: Container Model Results for Loading Scenario 3.

Table D.5 Continued

185	Loading Scenario 3	Original Container (M1)	Sidewalls Removed (M2)	Endwalls Removed (M3)	Roof Removed (M4)

	Container Stress <i>Exaggerated Deflection</i>
Yielding Location
		Bottom Face of Door Header by Corner Fittings (Rear Wall Removed for Clarity)	Bottom Face of Door Header by Corner Fittings (Deflection Exaggerated)	Door Header connection to Rear Corner Posts	Bottom Face of Door Header by Corner Fittings (displacement exaggerated)

Continued

Table D.5 Continued

186	Loading Scenario 3	Walls Removed (M5)	Single Sidewall Removed (M6)	Rear Wall Removed (M7)	Walls & Roof Removed (M8)

	Container Stress <i>Exaggerated Deflection</i>
Yielding Location
		Door Header connection to Rear Corner Posts	Bottom Face of Door Header by Corner Fittings (Rear Wall Removed for Clarity)	Door Header connection to Rear Corner Posts	Door Header connection to Rear Corner Posts

Continued

Table D.5 Continued

Loading Scenario 3		Maximum Applied Force & Displacement at Yielding	Deformed Shape of Container (Exaggerated Displacement with walls and roof removed)	Yielding Location (Circled in Red)	
M5		1117 - 1180 kN (251 - 265 kip) 11.18– 11.3 mm (0.44 in.)		Door Header connection to Rear Corner Posts	
M8
M3		996 - 1073 kN (241- 244 kip) 5.6 – 6.55 mm (0.22 – 0.26 in.)		Door Header at Rear Corner Posts	
M7
M6		942 – 977.7 kN (211.7–220 kip) 1.38 – 4.54 mm (0.05 – 0.18 in.)	M6 and M2	Bottom Face of Door Header by Corner Fittings	
M2
M1			M1 and M4		
M4

Loading Scenario 4	M1	M2	M4	M6	M7	M8	M5	M3

Maximum Applied Force (Each Corner Fitting)	150 kN (33.7 kip)	149.2 kN (33.5 kip)	141.1 kN (31.8 kip)	135.5 kN (30.4 kip)	57.5 kN (12.9 kip)	6.1 kN (1.4 kip)	5.6 kN (1.3 kip)	4.6 kN (1.03 kip)
Maximum Applied Force % Change from M1	---	-1%	-6%	-10%	-62%	-96%	-96%	-97%
Displacement	4.2 mm (0.17 in.)	4.28 mm (0.17 in.)	4.2 mm (0.17 in.)	3.85 mm (0.15 in.)	14.43 mm (0.57 in.)	36 mm (1.42 in.)	31.47 mm (1.24 in.)	11.57 mm (0.46 in.)
Stiffness	35.7 kN/mm (204 kip/in.)	34.9 kN/mm (199 kip/in.)	33.7 kN/mm (192 kip/in.)	35.2 kN/mm (201 kip/in.)	4.0 kN/mm (22.7 kip/in.)	0.17 kN/mm (0.97 kip/in.)	0.18 kN/mm (1.02 kip/in.)	0.40 kN/mm (2.3 kip/in.)
Stiffness % Change from M1	---	-2%	-6%	-1%	-88.9%	-99.52%	-99.5%	-98.9%
Simulation Time (seconds)	4023	3281	2896	4059	3061	1878	2762	2965

Continued

Table D.6: Container Model Results for Loading Scenario 4.

Table D.6 Continued

Loading Scenario 4	Original Container (M1)	Sidewalls Removed (M2)	Endwalls Removed (M3)	Roof Removed (M4)

Container Stress <i>Exaggerated Deflection</i>
Yielding Location
	Door Header at Top Corner Fitting (Closest to Loading)	Door Header at Top Corner Fitting (Closest to Loading)	Front Corner Post (opposite side of loading) at connection to Front Header	Door Header at Top Corner Fitting (Closest to Loading)

Continued

Table D.6 Continued

Loading Scenario 4	Walls Removed (M5)	Single Sidewall Removed (M6)	Rear Wall Removed (M7)	Walls & Roof Removed (M8)

Container Stress <i>Exaggerated Deflection</i>
Yielding Location
	Front Corner Post (opposite side of loading) at connection to Front Header	Door Header at Top Corner Fitting (Closest to Loading)	On Roof 1/3 distance from Rear (Door End) of container	Front Corner Post (opposite side of loading) at connection to Front Header

Continued

Table D.6 Continued

Loading Scenario 4		Maximum Applied Force & Displacement at Yielding	Deformed Shape of Container (Exaggerated Displacement with walls and roof removed)	Yielding Location (Circled in Red)	
M1		135.5 – 150 kN (30.4 – 33.7 kip) 3.85 – 4.28 mm (0.15 – 0.17 in.)		Door Header at Top Corner Fitting (Closest to Loading)	
M2			M4 only		
M4
M6
M7		57.5 kN (12.9 kip) 14.43 mm (0.57 in.)		On Roof 1/3 distance from Rear (Door End) of container	
M8		4.6 – 6.1 kN (1.03 – 1.4 kip) 11.57 - 36 mm (0.46 – 1.42 in.)		Front Corner Post (opposite side of loading) at connection to Front Header	
M5
M3

Loading Scenario 5	M4	M1	M3	M6	M7	M2	M5	M8

Maximum Applied Force (Each Corner Fitting)	124.5 kN (28 kip)	75 kN (16.9 kip)	75 kN (16.9 kip)	64.9 kN (14.6 kip)	48.9 kN (11 kip)	14.9 kN (3.4 kip)	13.75 kN (3.1 kip)	13.7 kN (3.07 kip)
Maximum Applied Force % Change from M1	+66%	---	0%	-13%	-35%	-80%	-82%	-82%
Displacement	4.32 mm (0.17 in.)	1.92 mm (0.08 in.)	1.94 mm (0.85 in.)	3.26 mm (0.13 in.)	1.53 mm (0.06 in.)	16 mm (0.63 in.)	15.88 mm (0.63 in.)	15.97 mm (0.63 in.)
Stiffness	28.82 kN/mm (165 kip/in.)	39.1 kN/mm (223 kip/in.)	38.7 kN/mm (220.1 kip/in.)	19.9 kN/mm (113.7 kip/in.)	32 kN/mm (183 kip/in.)	0.93 kN/mm (5.3 kip/in.)	0.87 kN/mm (4.94 kip/in.)	0.86 kN/mm (4.88 kip/in.)
Stiffness % Change from M1	-26%	---	-1%	-49%	-18%	-98%	-98%	-98%
Simulation Time (seconds)	2552	3200	2900	2782	4561	3214	2770	1881

Continued

Table D.7: Container Model Results for Loading Scenario 5.

Table D.6 Continued

Loading Scenario 5	Original Container (M1)	Sidewalls Removed (M2)	Endwalls Removed (M3)	Roof Removed (M4)

<div>Container Stress</div> <div>Exaggerated Deflection</div>
<div>Yielding Location</div>
	On Roof near top Front Corner Fittings	Front Corner Post connected to Base Side Rail	On Roof near top Front Corner Fittings	On Front Header Corner connected to Top Side Rails

Continued

Table D.6 Continued

194	Loading Scenario 5	Walls Removed (M5)	Single Sidewall Removed (M6)	Rear Wall Removed (M7)	Walls & Roof Removed (M8)

	Container Stress <i>Exaggerated Deflection</i>
Yielding Location
		Front Corner Post connected to Base Side Rail	On Roof near top Front Corner Fittings	Door Header connection to Roof and Top Side Rails	Front Corner Post connected to Base Side Rail

Continued

Table D.6 Continued

Loading Scenario 5		Maximum Applied Force & Displacement at Yielding	Deformed Shape of Container (Exaggerated Displacement with walls and roof removed)	Yielding Location (Circled in Red)
M4		124.5 kN (28kip) 4.32 mm (0.17 in.)		On Front Header Corner connected to Top Side Rails
M1		64.9 - 75 kN (14.6- 16.9 kip) 1.92 – 3.26 mm (0.08 - 0.85 in.)		On Roof near top Front Corner Fittings
M3
M6
M7		48.9 kN (11 kip) 1.53 mm (0.06 in.)		Door Header connection to Roof and Top Side Rails
M2		13.7 – 14.9 kN (3.07 – 3.4 kip) 16 mm (0.63 in.)		Front Corner Post connected to Base Side Rail
M5
M8

APPENDIX E
MODELING GUIDE WALKTHROUGH

STEP 1: Model Creation

Create Model Geometry in SolidWorks (2011)

Save File as .IGES (*.igs)

STEP 2: Importing into Hypermesh

Import .IGS file into Hypermesh (2009)

STEP 2 Continued

STEP 3: Meshing

Click the
Surface of the
Front Post
(It highlights
white)

STEP 3 Continued

12882 Elements Created

(Element Size = 1.0)

STEP 4: Mesh Quality Checks

Click Each Green Button to Check for Failed Elements

Most Element Quality Checks Failed

Warpage: 0 of 12898 (0%) failed

Aspect: 1500 of 12898 (12%) failed

Skew: 9223 of 12898 (71%) failed

Tet Collapse: 2 of 12898 (0%) failed

Quad Min Angle: no quads

Quad Max Angle: no quads

Length: varies

Jacobian: 0 of 12898 (0%) failed

Vol Skew: 7254 of 12898 (56%) failed

Vol AR: 1500 of 12898 (12%) failed

Tri Min Angle: 487 of 12898 (4%) failed

Tri Max Angle: 8 of 12898 (0%) failed

STEP 5: Delete Mesh

STEP 8: Mesh Corner Fitting Following Same Procedure

54287 Elements Created

(Element Size = 0.5)

STEP 9: Export Model to Create *.inp File

Ensure the Model Component's Labels do not contain Numbers

Click Red Arrow (Export)

STEP 9: Continued

The screenshot shows the 'Utility' dialog box in Abaqus/CAE. The 'File selection' section has 'File type' set to 'Abaqus', 'Template' set to 'Standard3D', and 'File' set to 'raduate Thesis-2009-2011\Example.inp'. The 'Export options' section has 'Export' set to 'All', 'Include connectors' checked, 'Write HM comments' checked, 'Include files' set to 'Merge', 'Prompt to save invalid elements' checked, and 'Prompt before overwrite' checked. The 'Export' button is circled in red.

Select Location for File

Click Export to create *.inp file

STEP 10: Import .inp File from Hypermesh into Abaqus/CAE (2010)

Open Abaqus/CAE (2010)

Select:
File > Import > Model

Find the *.inp file exported from
Hypermesh (2009) and Click OK

STEP 10: Continued

Imported Hypermesh Model in Abaqus/CAE (2010)

STEP 11: Create Material

Expand the Model Tree for Example

Double Click on “Materials”

STEP 11: Continued

Enter Name for Material

Click General Tab

Select “Density”

Enter a value of 7.85E-9

Click Mechanical Tab

Select “Elasticity” > Elastic

Enter a value of 200E3 for Young’s Modulus

Enter a value of 0.3 for Poisson’s Ratio

STEP 11: Continued

Click Mechanical Tab

Select “Plasticity” > Plastic

Enter a value of 343.3 for Yield Stress

Click OK to create Material

STEP 12: Create Section

Double Click “Sections” under Expanded Model Tree

Enter Name for Section

Select Category: “Solid”

Select Type: “Homogeneous”

Click Continue

Select Material Created in Step 11

Click OK

STEP 13: Assign Section to Imported Model

Expand Part in Model Tree

Double Click “Section Assignments”

Select the entire Model

Click Done

Select the Section Created in Step 12

Click OK and Done

STEP 14: Create Additional Step for Loading

Expand Example in Model Tree

Double Click “Steps”

Enter Name for Step

Click Continue

Leave Defaults (Linear Simulation)

Click OK

STEP 15: Create Constraint

Expand Example in Model Tree

Double Click “Constraints”

Enter Name for Constraint

Select “Tie” for Type

Click Continue

STEP 15 Continued

Select “Surface” for Master Type

Select the bottom and sides of the Corner Fitting’s Faces for the Master Surface Regions (Red)

Select “Surface” for Slave Type

Select the top of the Corner Post which touches the Corner Fitting (Purple)

Leave the Edit Constraint box with the defaults

Click OK

STEP 16: Create Loads for Simulation

Expand Example in Model Tree

Double Click “Loads”

Enter Name for Load
Select Step Created in Step 14

Load Type: Pressure

Select side face of Corner Fitting for “surface for the load” input

Click Done

STEP 16: Continued

Fill in Magnitude Value for Pressure Loading

Click OK

STEP 17: Create Boundary Condition

Expand Example in Model Tree

Double Click "BCs"

Enter Name for BC
Select Step Created in Step 14

Select the bottom face of the Corner Post for "regions for the boundary condition"

Select ENCASTRE (represents a fixed connection)

Click OK

STEP 18: Create Job

Expand Analysis in Model Tree

Double Click "Jobs"

Enter Name for Job

Select Model imported from Hypermesh

Leave Defaults for Edit Job Window

Click OK

STEP 19: Run Job Simulation

Expand the Job Tree

Right Click on Job Name created in Step 18

Click Submit

Right Click on Job Name Created in Step 18

Click Monitor

STEP 20: Check Results

Expand the Job Tree

Right Click on Job Name created in Step 18

Click Results

View the *.dat file for simulation warnings and errors

The field and history output can be viewed if it was created

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