University of Cincinnati

Date: 7/9/2019

I, Jueseok Kim, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

It is entitled:

Linear Finite Element Modeling of Joined Structures with Riveted Connections

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34301

Linear Finite Element Modeling of Joined Structures with Riveted
Connections

A thesis submitted to the Graduate School of
the University of Cincinnati
in partial fulfillment of requirements for the degree of

Master of Science

in the Department of Mechanical and Materials Engineering
of the College of Engineering & Applied Sciences

by

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July 2019

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Abstract

Riveted connections are widely used to join basic components, such as beams and panels, for engineering structures. However, accurately modeling joined structures with riveted connections can be a challenging task due to the riveting process of the connections. Solid rivets are ones of the most commonly used riveted connections. In the riveting process of a solid rivet, the rivet is inserted into matching holes of structural components to be joined, and a rivet setter and a bucking block are placed onto the rivet head and protruding end of the rivet shank, respectively. By simultaneously applying continuous loads to the rivet setter and holding the bucking block, the protruding end of the shank will be compressed and undergo plastic deformation. The riveting process of the rivet is concluded when the rivet shank is formed into a driven head. The riveting process is considered to be complex for two reasons. One reason is that the diameter of the shank increases due to its plastic deformation. The other reason is that surface contacts occur between the rivet and joined components and also between the joined components. In this work, an accurate linear finite element modeling method is proposed for joined structures with riveted connections. The proposed finite element modeling technique for a joined structure with riveted connections consists of two steps. The first step is to develop intensive finite element models that simulate the riveting process of solid rivets, where plastic deformations and surface contacts occurring to the rivets and components to be joined are considered. The second step is to develop a linear finite element model of the joined structure with the riveted connections simulated in the first step. The riveted connections are modeled using solid elements with dimensions and material

properties obtained from the intensive finite element models in the first step. An experimental investigation was conducted to study accuracy of the proposed finite element modeling method. A joined structure with riveted connections was prepared and tested; it had two aluminum strips that were joined by six identical aluminum solid rivets. A linearity check was conducted to validate that the joined structure could be considered to be linear. A linear finite element model of the joined structure was constructed using the proposed method. Natural frequencies and corresponding mode shapes of the joined structure were measured and compared with those from the linear finite element model. The maximum difference of the natural frequencies was 1.63% for the first 23 out-of-plane elastic modes, and modal assurance criterion values for the corresponding mode shapes were all over 95%, which indicates high accuracy of the proposed linear finite element modeling method.

Acknowledgement

I would first like to thank my thesis advisor Prof. Yongfeng Xu. The door to Prof. Xu office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it.

I would also like to acknowledge Structural Dynamics Research Lab facilities and faculties. Without their helps and the supports, I could not successfully finish this project.

Finally, I must express my very profound gratitude to my parents and to my spouse for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Contents

1	Introduction	1
2	Test Structure and Linearity Investigation	5
2.1	Test Structure Preparation	5
2.2	Linearity Investigation of Test Structure	10
3	FE Modeling Methodology	11
3.1	Intensive FE Models of Riveted Connections	14
3.2	Linear FE Model of Structure with Riveted Connections	16
4	Numerical and Experimental Investigations	20
4.1	Dimensions and Material Properties of Strips	20
4.2	Intensive FE Model Development	23
4.3	Linear Model Development	32
5	Experimental Validation of Linear FE Model	35
5.1	Experimental Procedure	35
5.2	Modal Parameter Estimation Results	36
6	Conclusions	38

List of Figures

1	(a) Strip to be joined for the test structure and (b) dimensions of the strip in (a).	7
2	(a) Dimensions of the solid rivet, and (b) definitions of the rivet head and rivet shank.	7
3	Rivet installation kit that includes an air-power hammer, a rivet setter and a bucking bar.	7
4	Test structure clamped by two bench vices and connected by five hand-tight bolted connections and one solid rivet to be installed.	8
5	Sketches of a solid rivet and strips to be joined, and positions of the bucking bar and rivet setter (a) before and (b) after the riveting process.	8
6	(a) Top view of the joined structure with riveted connections, (b) dimensions of the joined structure, (c) an enlarged view of the structure on the riveted connections, (d) a test setup of an impact test with free boundary conditions, (e) positions of measurement points on the joined structure, and (f) numbering of the measurement points in (e).	9
7	(a) Auto-power spectrum of a small-amplitude impact force and that of a large-amplitude impact force, and (b) measured FRFs of the joined structure associated with the impact forces in (a).	12
8	Measured FRF with Points 4 and 17 being the excitation and response measurement points, respectively, and that with Points 17 and 4 being the excitation and response measurement points, respectively.	13

9	Boundary conditions of the riveted connection in the intensive FE model.	16
10	Flow chart of developing an intensive finite element model to simulate a riveting process.	17
11	Impact test setup of one strip hung by two cotton ropes with positions of measurement and impact points indicated.	22
12	(a) Intensive FE model with meshed part, and (b) an enlarged view of a clearance between inserted part of rivet shank and matching holes of strips to be joined.	27
13	Surface numbering of parts for surface contact pairs.	28
14	Simulated riveting process at (a) $t = 0$ s (b) $t = 5.17$ s, (c) $t = 7.12$ s, (d) $t = 8.43$ s, (e) $t = 10$ s, and (f) $t = 20$ s.	29
15	Contact pressure distributions associated with the two strips in the load forming stage at different time instants.	30
16	Contact pressure distributions associated with the two strips in the load removing stage at different time instants.	30
17	Contact pressure distributions associated with the two strips with different friction coefficients at (a) $t = 10$ s and (b) $t = 20$ s.	31
18	(a) Meshed solid cylinder to model the riveted connection in linear FE model and (b) six solid cylinders tied to the two strips modeled using shell elements.	33

19	(a) First, (b) the second, (c) the third and (d) the fourth mode shapes of the joined structure, which were calculated from the linear finite element model; the (e) first, (f) second, (g) third and (h) fourth experimentally estimated mode shapes of the joined structure.	34
20	Sum of auto-power spectra of measured FRFs associated with the 39 measurement points.	37

List of Tables

1	Natural frequencies in Hz of the first nine elastic modes of the strip estimated from the impact test (“measured”), those from the finite element model with the nominal elastic modulus and poisson’s ratio (“before updating”), and those from the finite element model with the updated elastic modulus and Poisson’s ratio (“after updating”). Percentage errors between the natural frequencies from the finite element models and the measured ones are listed.	21
2	Natural frequencies in Hz of the first 23 out-of-plane elastic modes of the joined structure estimated from the linear finite element model (“calculated”) and those from an impact test (“measured”). Percentage errors between the calculated and measured natural frequencies are listed.	35
3	Percentage MPC values associated with measured mode shapes of the first 23 out-of-plane elastic modes of the joined structure.	38
4	Entries of the MAC matrix in percent corresponding to the first 23 out-of-plane elastic mode shapes of the joined structure estimated from the experimental modal analysis and those from the linear FE model; the horizontal and vertical mode numbers correspond to the experimentally estimated mode shapes and those from the linear FE model, respectively.	39

1. Introduction

In order to build complex engineering structures, various types of fasteners are needed to join various components together. While use of high-strength bolts are becoming more and more popular, riveted joints are still one of the most commonly used fasteners nowadays. Specifically, riveted joints are mainly applied with purposes in industry fields such as aircrafts, bridges, and building frames [1, 2]. Hence, assessing, maintaining and retrofitting existing components with riveted joints are important for structural designers and engineers. They need to be knowledgeable about riveted joints [1]. A riveted joint can consist of one or multiple riveted connections. There are different types of rivets in daily applications, including solid, self-piercing, and blind rivets, and solid rivets are one of the most reliable types of rivets [1, 3]. One typical application of solid rivets can be found in manufacturing structural components of aircraft by layering two or three sheets of materials and then joining them with solid rivets [4].

In recent studies, numerous finite element (FE) analysis results of structures with riveted connections have been presented. FE models of structures with riveted connections can be developed in two ways: three-dimensional and two-dimensional axisymmetric modeling. In three-dimensional modeling, detailed FE models with large numbers of elements are developed to simulate crashworthiness and joint failure tests of structures with riveted connections, where plastic deformations are considered. Langrand et al. [5] proposed a FE modeling method to investigate joint failure tests in airframe crashes using three-dimensional FE models. The FE modeling method can be used to optimize mechanical properties of joint components specifically for

airframe crash simulations. Rans et al. [6] developed a FE model to study residual stresses beneath a rivet head. The developed FE model is three-dimensional and quarter-symmetric, where eight-node brick elements were used. By simulating a riveting process, residual stresses beneath a rivet head were studied to show that they could be influenced by compression of joined sheets. Sadowski et al. [7] investigated a FE model of a hybrid joint with adhesive and a rivet to study effects of adding a rivet to an adhesive joint. In a developed FE model, a large number of elements were used to accurately evaluate large plastic deformations and contacts during a riveting process. Using adhesive riveted joints, the energy absorption could be increased by about 35%, comparing to an adhesive joint without a rivet. However, a major common issue of using three-dimensional FE models is that computation costs can be too high to afford due to large number of degrees of freedom.

Use of two-dimensional axisymmetric FE models can reduce numbers of degrees of freedom and enable accurate studies of effects of dimensions of rivets and applied loads during a riveting process. Hence, they can be considered to be computationally efficient with high accuracy as three-dimensional FE models. Quality of riveted connections can be affected by many parameters such as the applied loads during the riveting process, length of a rivet shank, diameter of the shank and matching hole diameter tolerance. Chiraghi [8] investigated effects of various aforementioned parameters in a countersunk riveting process using two-dimensional axisymmetric FE models. By decreasing the countersunk depth to 8.13×10^{-4} m from a recommended depth of 1.07×10^{-3} m, higher allowable ranges of matching hole and rivet diameters could be obtained. Also the range of applied loads could be increased without deteri-

orating quality requirements. Zhang et al. [9] proposed a mathematical model for a riveting process and verified it by use of a two-dimensional axisymmetric FE model. The mathematical study of a riveting process could accurately simulate deformations of thin-walled sheet-metal parts .

In contact models for connections in most mechanical joints, slip behaviors need considering since they can introduce non-linearities to structures with the joints. Segalman et al. [10] and Blake [11] investigated the mechanics of micro- and macro-slip behaviors and experimentally confirmed existence of slip behaviors. So far, uses of FE models of structures with riveted connections have focused on nonlinearity-related behaviors of structures with the connections, including studying crashworthiness of structures with riveted joints using three-dimensional elements, deformations of the structures, and the effect of applied loads and joint dimensions during a riveting process. However, a linear FE modeling method for modal parameters of structures with riveted connections is not available and needs developing. He and Zhu [12] developed two linear FE modeling approaches for structures with bolted connections. One approach is to update the elastic modulus of a bracket with bolted connections by comparing calculated and measured natural frequencies. The other approach is to use solid cylinders to model bolted connections. The two approaches can reduce number of degrees of freedom in developed FE models and yield accurate results.

In this work, a linear FE modeling method is proposed for structures with riveted connections. A test structure, which consisted of two aluminum strips joined by six aluminum solid rivets, was prepared. A linearity check of the joined structure was conducted to verify that it could be considered to be a linear structure. The

proposed FE modeling method for a joined structure with riveted connections consists of two steps; solid cylinders are used to model riveted connections. The first step is to develop an intensive two-dimensional axisymmetric model to simulate the riveting process of the riveted connections and determine dimensions and material properties of the solid cylinders. In the intensive model, plastic deformations and surface contacts are considered. The second step is to develop a linear FE model of the joined structure, where riveted connections are modeled using solid cylinders with dimensions and material properties determined in the first step. Experimental investigations of the proposed FE modeling method was conducted, where natural frequencies and modes shapes of the joined structure were estimated. Modal phase colinearity (MPC) values of the estimated mode shapes were calculated to validate that the joined structure had real modes. The estimated natural frequencies and mode shapes were compared with those from a linear FE model of the joined structure, which was developed using the proposed method.

The remaining part of this paper is outlined as follows. The preparation of the joined structure with riveted connections is described in Sec. 2.1. The investigation of linearity of the joined structure is presented in Sec. 2.2. Methodology for developing intensive and linear FE models for a structure with riveted connections are described in Secs. 3.1 and 3.2, respectively. Experimental estimation of material properties of the joined strips is presented in Sec. 4.1. Developments of an intensive FE model and a linear one are presented in Secs. 4.2 and 4.3, respectively. Results from the developed linear FE model were validated by those from an experimental modal analysis in Sec. 5. Conclusions of this work are presented in Sec. 6.

2. Test Structure and Linearity Investigation

In this section, a test structure with riveted connections was prepared, and it had two identical aluminum strips to be joined by six identical aluminum solid rivets. An experimental investigation of linearity of the joined structure was conducted, where linearity and reciprocity of its frequency response functions (FRFs) were checked.

2.1. Test Structure Preparation

One strip to be joined is shown in the Fig. 1(a), and it was made of aluminum 6061-T6511. Dimensions and matching hole positions of the strip are shown in Fig. 1(b); the strip had a thickness of 4.75×10^{-3} m. Dimensions of one solid rivet to join the strips are shown in Fig. 2(a). The rivet had a round-domed rivet head and a cylindrical rivet shank, and definitions of the rivet head and rivet shank are depicted in Fig. 2(b). Dimensions of the strips and rivets conformed to an engineering criterion for solid rivet installations: the diameter of a rivet shank needs to range between one to three times the thickness of a strip to be joined [11].

The test structure with the six riveted connections was prepared using a rivet installation kit shown in Fig. 3, including a McMaster-Carr style-B air-power hammer, a rivet setter and a bucking bar. The rivet setter was a bit to be inserted into the barrel of the air-power hammer. The rivet setter was selected based on the shape and size of the rivet head. The rivet setter had a convex-rounded tip, which could engage the rivet heads in the riveting process, and continuous loads from the air-power hammer could be evenly applied to the rivet heads in the riveting process. Otherwise, the rivet would be damaged due to unevenly applied loads. The bucking

bar was a solid iron block to be placed at the end of the rivet shank to provide support for the rivet.

Prior to the riveting process, the two strips were clamped by two bench vices, and they were joined by six bolts with hand-tight nuts. As shown in Fig. 4, the riveting process of one rivet was started by replacing one of the bolts with a rivet, while keeping other bolts in place to prevent slips between the strips that might lead to misalignments of matching holes of the strips, as shown in Fig. 5(a). The rivet setter inserted into the air-power hammer and the bucking bar were placed onto the rivet head and the other end of the rivet shank, respectively. By applying continuous loads in the form of impacts to the rivet head using the air-power hammer and fixing the bucking bar, the protruding part of the rivet shank was gradually formed into a driven head, which concluded the riveting process of one solid rivet as shown in the Fig. 5(b). Other five rivets were installed in the same way, and preparation of the test structure was finished as shown in Fig. 6(a). Dimensions of the joined structure are shown in the Fig. 6(b), and an enlarged view of the riveted connections is shown in the Fig. 6(c). Thicknesses of the driven heads of the six installed rivets were measured, and their average was 2.60×10^{-3} m.

Figure 1: (a) Strip to be joined for the test structure and (b) dimensions of the strip in (a).

Figure 2: (a) Dimensions of the solid rivet, and (b) definitions of the rivet head and rivet shank.

Figure 3: Rivet installation kit that includes an air-power hammer, a rivet setter and a bucking bar.

Figure 4: Test structure clamped by two bench vices and connected by five hand-tight bolted connections and one solid rivet to be installed.

Figure 5: Sketches of a solid rivet and strips to be joined, and positions of the bucking bar and rivet setter (a) before and (b) after the riveting process.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 6: (a) Top view of the joined structure with riveted connections, (b) dimensions of the joined structure, (c) an enlarged view of the structure on the riveted connections, (d) a test setup of an impact test with free boundary conditions, (e) positions of measurement points on the joined structure, and (f) numbering of the measurement points in (e).

2.2. Linearity Investigation of Test Structure

The linearity of the joined structure in Fig. 6(a) was experimentally investigated by checking linearity and reciprocity of its FRFs. Free boundary conditions of the joined structure were simulated by two identical rubber bands that supported the two joined strips near their ends, as shown in Fig. 6(d). A grid with 3×13 measurement points was assigned to the joined structure, and numbering and positions the points are shown in the Fig. 6(e). An impact hammer, PCB 068C05, was used to excite the joined structure in the form of single impacts. A scanning laser Doppler vibrometer Polytec PSV-500-Extra was used to measure response of the joined structure at the measurement points. The excitation and response measurement were in $-z$ and $+z$ directions, respectively, as indicated in Fig. 6(e). In this investigation, the joined structure was excited at Point 4 with two different impact magnitudes as shown in Fig. 7(a), and responses at Point 20 were measured by the vibrometer. Two FRFs between the two single impacts and corresponding responses were estimated and compared in the Fig. 7(b). It can be seen that magnitudes of the two FRFs almost overlap in the measured frequency range between 0 and 2,300 Hz. The frequency response assurance criterion (FRAC) value between the two estimated FRFs was 96.5% [13], indicating that they were highly correlated and FRFs of the joined structure could be considered to be linear. A reciprocity check of the joined structure was conducted by comparing reciprocal FRFs associated with Points 4 and

17. As shown in the Fig. 8, magnitudes of the reciprocal FRFs overlap each other, and their associated FRAC value was 94.4%. Based on the linearity and reciprocity check results, the joined structure could be considered to be linear within the measured frequency range. It was implied that existence of the riveted connections would not effect the linearity of the joined structure and modal parameters of the structure could be numerically and experimentally estimated from a linear FE model and modal analysis, respectively. This implication is similar to that for structures with bolted connections, which can be considered to be linear within a certain frequency range [12].

3. FE Modeling Methodology

Even though linearity of the joined structure had been experimentally validated, it could not be immediately modeled by a linear FE model with high accuracy due to the riveting process, where surface contacts and plastic deformations had occurred. In order to develop an accurate linear FE model of a joined structure with riveted connections like the test structure, a two-step FE modeling technique is proposed. The first step is to develop intensive FE models that simulate the riveting process of the riveted connections, where surface contacts and plastic deformations are considered. The second step is to develop a linear FE model of the structure, whose riveted connections are modeled by linear solid cylinders. Dimensions and material

(a)

(b)

Figure 7: (a) Auto-power spectrum of a small-amplitude impact force and that of a large-amplitude impact force, and (b) measured FRFs of the joined structure associated with the impact forces in (a).

Figure 8: Measured FRF with Points 4 and 17 being the excitation and response measurement points, respectively, and that with Points 17 and 4 being the excitation and response measurement points, respectively.

properties of the solid cylinders are determined using results from the intensive FE models. Joined components of the structure are modeled using linear elements that are tied to the solid cylinders. In this work, the commercial FE analysis software ABAQUS is used for FE modeling and analysis.

3.1. Intensive FE Models of Riveted Connections

The objective of developing intensive FE models that simulate riveting processes is to obtain dimensions and material properties of solid cylinders, which are used to model riveted connections in the linear FE model. To achieve the objective, the developed FE models need to have high accuracy. However, developing such FE models can be challenging for the following three reasons. The first reason is that nonlinear plastic deformations occur to a solid rivet during its riveting process, where the protruding part of its shank is formed into a driven head as shown in Fig. 5. Due to the plastic deformations, the diameter of a rivet shank will increase. As a result, the clearance, which exists between the rivet shank and matching holes of joined components before the riveting process, will be filled. Besides, the volume of the rivet is changed by applied loads, so is the density of the installed rivet. The second reason is that surface contacts occur between the rivet and joined components and between the joined components themselves in the riveting process. The third reason is that the required number of degrees of freedom of an accurate intensive three-dimensional FE model for the riveting process can be too high to be computationally efficient. To address the first and second reasons, plastic deformations and surface contacts are considered in intensive FE models to be developed. To address the third reason, the intensive FE models use axisymmetric two-dimensional elements.

In an intensive FE model that simulates a riveting process, a rivet, a rivet setter, a bucking bar and components to be joined are parts that constitute a riveted connection, and they are modeled using axisymmetric two-dimensional elements assigned with respective material properties, including mass densities, elastic moduli, Poisson's ratios and plastic stress-strain relations. To simulate the process, surface contacts between the parts and their plastic deformations are enabled. The modeled parts are assembled to appropriate positions. Boundary conditions are defined: the bottom surface of the rivet setter is vertically fixed and the edge of the rivet along the axis of symmetry is radially fixed, as shown in Fig. 9, where x - and y -axis represent radial and vertical directions in the cylindrical coordinate system, respectively. The riveting process in simulated the intensive FE model can be divided into two stages: a load forming stage and a load removing stage. The load forming stage is achieved by slowly moving the bucking bar downward along y -axis to a desired position. The movement of the bucking bar is so slow that the load forming stage can be considered to be quasi-static. When the bucking bar arrives at the desired position so that the driven head is under no loads from the bucking bar, the protruding part of the rivet shank is formed into a driven head. The load removing stage is achieved by moving the bucking bar upward along y -axis to a desired position, which concludes the development of the intensive FE model. From the developed intensive FE model, one can quantitatively observe the aforementioned surface contacts and plastic deformations of the rivet and joined components, with which dimensions and material properties of solid cylinders for a linear FE model can be determined. A flowchart that describes the development procedure of the intensive model is shown

Figure 9: Boundary conditions of the riveted connection in the intensive FE model.

in Fig. 10.

3.2. Linear FE Model of Structure with Riveted Connections

Based on results from the intensive FE models of the riveted connections, a linear FE model of the joined structure can be developed. In the linear FE model, the riveted connections are equivalently modeled by solid cylinders of solid elements. Dimensions of the solid cylinders are obtained from the intensive FE models. The radius of one solid cylinder is equal to the sum of the radius of matching holes of

Figure 10: Flow chart of developing an intensive finite element model to simulate a riveting process.

the joined components and an effective dimension of the contact area associated the joined component. Specifically, the effective dimension is defined as the difference between the outer and inner radii of the contact area. The height of the solid cylinder is equal to the sum of thicknesses of the joined components, and it is denoted by L_s .

Since the volume of an installed solid rivet is changed due to its plastic deformations, the mass density of the rivet will change. The mass density of the solid cylinder in the linear FE model can be calculated by

$$\rho_s = \frac{M_r + M_j}{V_s} \quad (1)$$

where M_r is the mass of a portion of the installed rivet, which is embedded in the matching holes, M_j is the mass of portions of the joined components that are in contact, and V_s is the volume of the solid cylinder, which can be calculated using the dimensions of the solid cylinder. Meanwhile, mass densities of the formed driven head and round-domed rivet head are assumed to be unchanged, i.e., those of the rivet before its riveting process. The equivalent elastic modulus of the solid cylinder can be calculated using Hooke's law [11]:

$$E_s = k_s \frac{L_s}{A_s} \quad (2)$$

where

$$A_s = A_r + A_j \quad (3)$$

is the cross-sectional area of the solid cylinder, in which A_r and A_j are the cross-

sectional area of the installed rivet and the contact area, respectively, and k_s is the equivalent stiffness of the solid cylinder. The equivalent stiffness can be obtained as a sum of stiffnesses of two parallelly connected springs:

$$k_s = k_r + k_j \quad (4)$$

where k_r and k_j are stiffnesses corresponding to the portion of the installed rivet and the portion of the joined components that are in contact, respectively. The two stiffnesses can be calculated by

$$k_r = \frac{E_r A_r}{L_s} \quad (5)$$

where E_r is the elastic modulus of the rivet, and

$$k_j = \frac{E_j A_j}{L_s} \quad (6)$$

where E_j is the elastic modulus of the joined components. Meanwhile, elastic moduli of the formed driven head and the round-domed rivet head are assumed to be unchanged and equal to those of the rivet before the riveting process. Portions of the joined components beyond the contact areas are tied to the solid cylinders. The developed linear FE model of the joined structure can be used to accurately estimate its natural frequencies and mode shapes.

4. Numerical and Experimental Investigations

4.1. Dimensions and Material Properties of Strips

Dimensions and material properties of the two identical strips of the joined structure in Fig. 6(a), including elastic modulus, Poisson's ratio and mass density, were experimentally studied before the riveting process. Dimensions of one of the strips were measured as shown in Fig. 1(b); the thickness of the strips was measured to be 4.75×10^{-3} m. The mass density of the strip was measured to be 2.67×10^3 kg/m³, which was calculated by dividing its total mass by its volume that was calculated based on its measured dimensions. Poisson's ratio of the strip was 0.33 and elastic modulus was 69.0 GPa, which were nominal values of aluminum 6061-T6511. A FE model of the strip was developed with 43,400 quadratic triangular shell (STR165) elements. Free boundary conditions were applied to the strip in the model. Natural frequencies of the strip were calculated and listed in Table 1.

An impact test of one strip was conducted to estimate natural frequencies of the strip. The strip was hung using two cotton ropes to simulate free boundary conditions, as shown in Fig. 11. Impacts and responses were generated and measured using the same impact hammer and vibrometer in Sec. 2.1, respectively. One impact point and nine measurement points were randomly selected as indicated in Fig. 11. Nine FRFs associated with the nine measurement points and the impact point were measured. Each FRF was obtained with five averages. The nine FRFs were then analyzed by a modal parameter estimation algorithm, PolyMax in LMS Test.Lab 17, to estimate natural frequencies of the first nine out-of-plane elastic modes of the strip, which are listed in Table 1. The free boundary conditions of the strip were

Table 1: Natural frequencies in Hz of the first nine elastic modes of the strip estimated from the impact test (“measured”), those from the finite element model with the nominal elastic modulus and poisson’s ratio (“before updating”), and those from the finite element model with the updated elastic modulus and Poisson’s ratio (“after updating”). Percentage errors between the natural frequencies from the finite element models and the measured ones are listed.

Mode	Measured	Before Updating	Error	After Updating	Error
1	65.905	68.039	3.136	66.562	0.987
2	180.438	187.14	3.581	182.95	1.389
3	353.153	366.38	3.610	357.89	1.324
4	471.943	467.91	-0.862	462.94	-1.945
5	583.406	605.14	3.592	590.57	1.213
6	690.25	710.37	2.832	685.53	-0.689
7	871.719	903.67	3.536	880.68	1.018
8	947.925	938.73	-0.980	940.77	-0.761
9	1218.25	1262.4	3.497	1228.7	0.850

validated, since the highest measured natural frequency of the rigid-body modes was 1.89 Hz, which is less than 10% of the natural frequency of the first elastic mode, i.e., 65.905 Hz [14].

Comparing the natural frequencies from the FE model and the impact test, the maximum percentage error was 3.61 %. The reason was that the nominal values of the elastic modulus and Poisson’s ratio of the strip in the FE model were not accurate. To reduce the error, elastic modulus and Poisson’s ratio were updated and applied to the FE model. By updating the elastic modulus to 66.0 GPa and Poisson’s ratio to 0.30, the maximum percentage error for the natural frequencies of the nine elastic modes decreased to 1.94%, as shown in Table 1.

Figure 11: Impact test setup of one strip hung by two cotton ropes with positions of measurement and impact points indicated.

4.2. Intensive FE Model Development

To develop an intensive FE model of a riveted connection of the joined structure in Fig. 6(b), five structural parts were developed: a bucking bar, two strips to be joined, a solid rivet and a rivet setter. The rivet is meshed using 850 axisymmetric four-node bilinear (CAX4R) elements. Elements on edges of the meshed rivet were finer than those along the axis of symmetry, since the former would undergo surface contacts during a riveting process. Each of the two strips were meshed with 720 CAX4R elements. In the FE model, the solid rivet, which was made of aluminum 1100, had a nominal mass density of $2.70 \times 10^3 \text{ kg/m}^3$, Poisson's ratio of 0.33 and nominal elastic modulus of 69.0 GPa. The strips, based on results from Sec. 4.1, had a mass density of $2.68 \times 10^3 \text{ kg/m}^3$, Poisson's ratio of 0.30 and elastic modulus of 66.0 GPa. The bucking bar and rivet setter, which were made of steel, had a mass density of $8 \times 10^3 \text{ kg/m}^3$, Poisson's ratio of 0.25 and elastic modulus of 200 GPa. In addition, the rivet and strips had a plastic stress-strain relation of aluminum alloy [15]. The meshed parts were assembled to appropriate positions for a riveting process, as shown in Fig. 12(a), and a clearance between the rivet and strips can be observed in Fig. 12(b). Surface contacts were defined to numbered surface pairs: (1)-(2), (1)-(3), (3)-(4), (3)-(5), (3)-(8), (6)-(7), (9)-(10), (9)-(12) and (11)-(13), as indicated in Fig. 13. Normal and frictional surface contact properties of the above contact surface pairs were defined as follows. For the normal surface contact property, any penetration between two surfaces in contact was not allowed, and separation of surfaces that had once been in contact was allowed. For the frictional surface contact property, friction coefficients were defined: 0.61 for contact between aluminum and steel surfaces and

1.05 for contact between the aluminum surfaces [16]. The boundary conditions were defined: radial displacements of nodes on the edge of the meshed rivet along the axis of symmetry were constrained and the bottom of the rivet setter was constrained as shown in Fig. 9. Since the intensive model was developed with axisymmetric elements, it had a cylindrical coordinate system, where x - and y -axis respectively denote the radial and vertical directions of the intensive FE model in Fig. 9.

The riveting process was simulated in two stages, including a load forming stage and a load removing stage, as described in Sec. 3.1. The load forming stage had a duration of 10 s, in which the bucking bar moved downward to a desired position, which was -7.22×10^{-3} m along y -axis from its original position. In Figs. 14(a) through (e), the load forming stage is visually depicted by the FE model at five different time instants. The load forming stage started at $t = 0$ s that corresponded to Fig. 14(a) and it ended at $t = 10$ s that corresponded to Fig. 14(e). Plastic deformations during the load forming stage could be observed at the protruding part of rivet shank when the driven head was being squeezed by the bucking bar, as shown in Figs. 14(b) through (d). Due to the plastic deformations, the clearance between the rivet and strips was filled up, and the radius of the rivet shank increased from 3.20×10^{-3} m to 3.22×10^{-3} m at $t = 10$ s. Contact pressure distributions between the two strips along the radial direction at the five time instants are shown in Fig. 15. Surface contacts were considered to occur within areas that had non-zero contact pressures. Note that in Fig. 15 the origin of the horizontal axis was at 3.42×10^{-3} m instead of 3.22×10^{-3} m, which was the radius of the hole on the joined strips at $t = 0$. The reason was that nodes of the two joined components at their holes were also in

contact with the inserted part of the rivet shank and one could not differentiate the contact pressures given by the rivet from that given by the strips. As shown in the Fig. 15, the maximum contact pressure occurred at the nodes closest to the edge of the holes, and it gradually increased with time. At $t = 10$ s, the effective dimension of the contact area was measured to be 7×10^{-3} m and the radius of the inserted part of the rivet shank was measured to be 3.328×10^{-3} m, which concluded the load forming stage.

The load removing stage had a duration of 10 s, in which the bucking bar moved upwards to its original position in the first stage. As shown in Figs. 14(e) and (f), the load removing stage started at $t = 10$ s that corresponded to Fig. 14(e), and it ended at $t = 20$ s that corresponded to Fig. 14(f). Contact pressure distributions between the two strips along the radial direction at different time instants in the load removing stage are shown in Fig. 16. It could be observed that the contact pressures along the radial direction decreased with time and the effective dimension changed from 7×10^{-3} m to 1.6×10^{-3} m at $t = 20$ s; the latter effective dimension was considered to be the final effective dimension of the contact area. The reason was that moving the bucking bar upwards resulted in removal of the applied loads and the formed rivet connection would stretch to a new equilibrium position. The radius of the inserted part of the rivet shank decreased from 3.328×10^{-3} m to 3.315×10^{-3} m. Note that in Fig. 16, the origin of the horizontal axis was at 3.515×10^{-3} m instead of 3.315×10^{-3} m, which was the final radius of the inserted part of the rivet shank at $t = 20$ s in the load removing stage. The driven head had a thickness of 2.60×10^{-3} m at the end of the load removing stage, i.e, $t = 20$ s, as shown in Fig.

14(f), and the thickness was equal to the average measured thickness of the six driven heads of the test structure in Sec. 2.1. An extra stage of simulation was added here to study the effective dimension, and it had a duration of 10 s. In the extra stage, no parameters were changed since the load removing stage, and the contact pressure distribution at $t = 25$ s and $t = 30$ s are shown in Fig. 16. The contact pressure distributions were observed to be unchanged throughout the stage.

A parametric study of the friction coefficient was conducted for the effective dimension of the contact area. The studied friction coefficient was the one associated with the contact between the aluminum parts, including the rivet and the strips. The studied friction coefficient varied between 0.85 and 1.45 with an increment of 0.20. The contact pressure distributions between the two strips along the radial direction at $t = 10$ s, and $t = 20$ s are shown and compared in Figs. 17(a) and (b), respectively. In Figs. 17(a) and (b), the contact pressure distributions for four cases compared well with each other along the radial direction, which indicates that the change of the friction coefficient in the range would not affect the contact pressure distributions. More importantly, the effective dimension of the contact area would not be changed by the change of the friction coefficient.

Figure 12: (a) Intensive FE model with meshed part, and (b) an enlarged view of a clearance between inserted part of rivet shank and matching holes of strips to be joined.

Figure 13: Surface numbering of parts for surface contact pairs.

Figure 14: Simulated riveting process at (a) $t = 0$ s (b) $t = 5.17$ s, (c) $t = 7.12$ s, (d) $t = 8.43$ s, (e) $t = 10$ s, and (f) $t = 20$ s.

Figure 15: Contact pressure distributions associated with the two strips in the load forming stage at different time instants.

Figure 16: Contact pressure distributions associated with the two strips in the load removing stage at different time instants.

(a)

(b)

Figure 17: Contact pressure distributions associated with the two strips with different friction coefficients at (a) $t = 10$ s and (b) $t = 20$ s.

4.3. Linear Model Development

Each of the six riveted connections in the joined structure was modeled by a solid cylinder with a round-domed rivet head and a driven head using 10,695 ten-node quadratic tetrahedral (C3D10) elements as shown in the Fig. 18.

Dimensions of the solid cylinders were obtained from the riveted connection in the intensive FE model for the riveting process. Specifically, the height of one solid cylinder was equal to twice the thickness of the strips and its radius is equal to sum of the final radius of the inserted part of the rivet shank, i.e., 3.315×10^{-3} m, and the final effective dimension of the contact area between the two strips, i.e., 1.6×10^{-3} m; the sum was equal to 4.915×10^{-3} m. The mass density of the solid cylinder was calculated to be 2.722×10^3 kg/m³, based on Eq. (1); the elastic modulus of the solid cylinder was calculated to be 67.34 GPa, based on Eq. (2). The mass densities and elastic modulus of the formed driven head and domed rivet head remained the same as those before the riveting process, which were 2.79×10^3 kg/m³ and 69 GPa, respectively. Shell elements were used to model the two strips. A total of 4,146 linear triangular shell (S3) elements were used for one strip, which was the case of the other strip. Material properties of the strips, including the mass density, elastic modulus and Poisson's ratio, in the linear FE model were those experimentally obtained in Sec. 4.1. The solid cylinders are tied to the joined strips, based on two reasons. One reason was that non-zero contact pressure distributions

Figure 18: (a) Meshed solid cylinder to model the riveted connection in linear FE model and (b) six solid cylinders tied to the two strips modeled using shell elements.

along the contact surfaces between the rivet shank and the two strips were observed, which could lead to permanent contacts between the rivet and joined strips. The other reason was that from the results of the linearity investigation of the joined structure in Sec. 2.2, non-linear macro-slip behavior did not occur after the riveting process and non-linearity caused by micro-slip could be neglected [10, 11]. Natural frequencies of the first 23 out-of-plane elastic modes of the joined structure in the linear FE model are calculated and listed in Table 2. Mode shapes associated with the first four out-of-plane elastic modes are shown in Fig. 19.

Figure 19: (a) First, (b) the second, (c) the third and (d) the fourth mode shapes of the joined structure, which were calculated from the linear finite element model; the (e) first, (f) second, (g) third and (h) fourth experimentally estimated mode shapes of the joined structure.

Table 2: Natural frequencies in Hz of the first 23 out-of-plane elastic modes of the joined structure estimated from the linear finite element model (“calculated”) and those from an impact test (“measured”). Percentage errors between the calculated and measured natural frequencies are listed.

Mode	Calculated	Measured	Error	Mode	Calculated	Measured	Error
1	18.555	18.373	0.99	13	892.965	883.870	1.03
2	51.8257	50.932	1.75	14	934.735	940.444	-0.61
3	98.8758	97.645	1.26	15	1111.53	1097.375	1.29
4	167.286	164.607	1.63	16	1257.84	1247.297	0.85
5	247.557	244.49	1.25	17	1299.71	1317.507	-1.35
6	256.835	260.526	-1.42	18	1436.11	1454.758	-1.28
7	347.073	342.048	1.47	19	1541.01	1520.596	1.34
8	454.108	461.523	-1.61	20	1684.51	1672.169	0.74
9	465.167	459.285	1.28	21	1840.34	1863.541	-1.24
10	589.409	582.101	1.26	22	1969.48	1993.632	-1.21
11	752.955	743.445	1.28	23	2040.9	2010.398	1.52
12	773.651	785.026	-1.45				

5. Experimental Validation of Linear FE Model

To validate the linear FE model, an experimental modal analysis of the joined structure was conducted with the same setup for its linearity investigation, which was described in Sec. 2.2.

5.1. Experimental Procedure

The experimental modal analysis was conducted using the roving sensor technique, where one impact point and the 39 measurement points were selected [14]. The position of the impact point is shown in Fig. 6(e). The location of the impact point was determined based on the first 23 out-of-plane elastic mode shapes from

the linear FE model to avoid most nodal lines. Random errors, such as measurement noise and inconsistent impact locations, were minimized by power spectra averaging. Bias errors, such as leakage, were minimized by applying appropriate windows to excitation and response measurement data. At each measurement point, five sets of excitation and response measurement data were collected and used to calculate the associated averaged FRF with the H-1 algorithm [13]. Each set of measurement data had a duration of 10.24 s and was collected with a sampling frequency of 5,000 Hz; the frequency resolution of a FRF was 9.766×10^{-2} Hz. A force window and an exponential window were applied to the collected excitation and response measurement data, respectively.

5.2. Modal Parameter Estimation Results

FRFs associated with the 39 measurement points were analyzed by the modal parameter estimation algorithm, PolyMax in LMS Test.Lab 17. The sum magnitudes of the analyzed 39 FRFs is shown in the Fig. 20 to assist identification of the elastic modes. The number of peaks in the Fig. 20 could indicate the number of elastic modes of the joined structure within the Nyquist frequency associated with the sampling frequency, i.e., 2,500 Hz. Free boundary conditions had been validated in the linearity investigation in Sec. 2.2. Based on the measured FRFs, estimated natural frequencies and mode shapes associated with the first 23 out-of-plane elastic modes of the joined structure were obtained. The estimated natural frequencies are listed in Table 2 and compared with those from the linear FE model. It can be seen that the maximum percentage error was 1.63% for the 23 out-of-plane elastic modes. The estimated mode shapes associated with the first four out-of-plane elastic

Figure 20: Sum of auto-power spectra of measured FRFs associated with the 39 measurement points.

modes are shown in Figs. 19(e) through (h). Modal vector complexity associated with the 23 estimated mode shapes was quantified using MPC values, which served to check degrees of complexity of complex mode shapes [17]. The MPC values for the 23 mode shapes are listed in Table 3, and they were all over 99%. Such high MPC values indicated that the 23 out-of-plane elastic modes were all real modes, which was the case of the joined structure in the linear FE model. A modal assurance criterion (MAC) matrix between the first 23 out-of-plane mode shapes from the linear FE model and the experimentally estimated ones was calculated and listed in Table 4. It could be seen that all diagonal MAC entries were over 95%, indicating that the mode shapes of the same modes were highly correlated. Based on the comparison of the natural frequencies and MAC matrix, accuracy of the linear FE model of the prepared joined structure was experimentally validated.

Table 3: Percentage MPC values associated with measured mode shapes of the first 23 out-of-plane elastic modes of the joined structure.

Mode	MPC	Mode	MPC
1	99.969	13	99.841
2	99.969	14	99.737
3	99.923	15	99.861
4	99.855	16	99.827
5	99.865	17	99.84
6	99.911	18	99.634
7	99.874	19	99.858
8	99.85	20	99.847
9	99.857	21	99.774
10	99.951	22	99.631
11	99.856	23	99.83
12	99.944		

6. Conclusions

In this work, a linear FE modeling method for structures with riveted connections was proposed, and its accuracy for modal parameter estimation was experimentally validated. The developed modeling method has two steps. The first step is to develop intensive FE models that accurately simulate riveting processes of riveted connections of a joined structure. In the intensive models, two-dimensional axisymmetric elements are used and plastic deformations and surface contacts that occur during the riveting processes are considered. The second step is to develop a linear FE model of the joined structure. In the linear FE model, formed riveted connections were modeled by solid cylinders, driven heads and rivet heads. Dimensions and material properties of the solid cylinders, driven heads and rivet head are estimated

Table 4: Entries of the MAC matrix in percent corresponding to the first 23 out-of-plane elastic mode shapes of the joined structure estimated from the experimental modal analysis and those from the linear FE model; the horizontal and vertical mode numbers correspond to the experimentally estimated mode shapes and those from the linear FE model, respectively.

Mode	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	100	13	3	10	0	1	10	1	3	7	1	1	8	0	3	6	0	0	2	7	0	0	8
2	13	100	10	1	9	0	1	0	8	2	8	1	2	0	4	3	0	0	6	3	0	0	6
3	2	10	100	10	4	0	7	0	1	8	5	0	5	0	1	8	0	0	9	3	0	0	3
4	10	1	9	100	8	0	2	0	8	2	7	0	3	0	4	3	0	1	6	5	0	0	3
5	0	9	3	7	100	0	7	0	6	5	2	0	5	0	5	5	0	1	3	5	0	0	19
6	0	0	0	0	0	98	0	5	0	0	0	0	0	3	0	0	0	3	0	0	0	4	0
7	9	1	7	1	8	0	100	1	6	3	5	0	2	0	3	6	0	0	4	4	0	0	7
8	1	0	0	0	0	4	0	96	1	0	0	5	0	3	0	0	3	1	0	0	4	1	0
9	2	8	0	7	4	0	5	4	97	5	7	0	3	0	2	5	0	0	17	1	0	1	57
10	6	1	8	1	6	0	2	0	5	99	5	0	6	0	3	4	0	0	6	64	0	0	38
11	0	6	4	6	1	0	5	0	6	3	99	0	4	0	10	2	0	0	58	27	0	0	2
12	0	1	0	0	0	0	0	4	0	0	0	98	0	5	0	0	0	3	0	0	0	3	0
13	6	1	5	3	6	0	1	0	5	4	4	0	99	0	3	78	0	0	36	1	0	0	6
14	0	0	1	0	0	2	0	2	0	0	0	6	0	98	0	0	5	1	0	0	2	0	0
15	3	3	0	3	4	0	3	0	1	2	8	0	1	0	99	24	0	0	2	9	0	0	0
16	5	3	7	2	5	0	6	0	8	2	4	0	73	0	30	99	0	0	15	2	0	0	4
17	0	0	0	1	0	0	0	4	0	0	0	0	0	4	0	0	98	4	0	0	0	3	0
18	0	0	0	0	1	3	0	1	0	0	0	3	0	1	0	0	6	98	0	0	5	1	0
19	1	4	9	4	2	0	4	1	16	5	48	0	41	0	4	13	0	0	97	3	0	0	3
20	5	2	2	5	4	0	2	0	2	59	34	0	2	0	8	3	0	0	7	98	0	0	7
21	0	0	0	0	0	0	1	4	0	0	0	0	0	3	0	0	0	4	0	0	98	4	0
22	0	0	0	0	0	4	0	1	0	0	0	3	0	1	0	0	3	1	0	0	8	98	1
23	9	3	1	2	17	0	3	2	43	36	5	0	9	0	1	7	0	0	1	4	0	1	95

based on results from the intensive models. In addition, joined components can be modeled using simple elements, such as plate/shell elements. To experimentally investigate the proposed method, a joined structure was prepared, which had two identical aluminum strips. The two strips were joined by six identical solid rivets that were installed using a rivet installation kit. Linearity of the joined structure was experimentally validated. Modal parameters, including natural frequencies and mode shapes, of its first 23 out-of-plane elastic modes of the joined structure were estimated based on its measured FRFs. A linear FE model of the joined structure was developed based on the proposed modeling method to numerically estimate its natural frequencies and mode shapes. A parametric study of the friction coefficient between aluminum parts in the joined structure was conducted. It was found that changes of the friction coefficient would have negligible effects on contact pressure distributions and dimensions of a solid cylinder. The maximum error between the experimentally and numerically estimated natural frequencies was 1.63% and all diagonal entries of a MAC matrix that corresponded to the experimentally and numerically estimated mode shapes were all over 95%. The relatively low percentage error and high MAC values indicate that the joined structure could be accurately modeled to estimate its modal parameters. It was also experimentally shown that the estimated mode shapes had high MPC values, indicating that the estimated modes were real modes, which was the case of the joined structure in the linear FE model.

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