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Validation of finite element models of structures with riveted joints using vibration data

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ABSTRACT

Rivets are used as fasteners for joining metal parts together in many industrial applications, especially those in aerospace industry. They are particularly useful for joining sheet metals. However, modelling structures assembled using such joints is still quite difficult due to the fact that riveted joints rely on contact forces to maintain the joints and this, in general, causes non-linear behaviour. Furthermore, a typical structure may contain excessive number of riveted joints and this may well prohibit including realistic non-linear contact forces in theoretical models.

This paper aims to determine whether an acceptable linear Finite Element (FE) model can be built by adjusting the FE models using the measured modal properties of structures with riveted joints. This is done by first validating the material properties of a structure without any riveted joints. Then, some structures with riveted joints are modelled by assuming that a rivet is effectively clamping the matching surfaces around it within a specified diameter. After that, experimental modal analyses are performed on these structures so as to obtain the modal properties. The measured modal data are then used to adjust the effective clamping diameter of the rivets in order to minimize the error between the predicted and the measured natural frequencies and mode shapes.

1 INTRODUCTION

Obtaining a validated theoretical model of structures is very important for design and optimisation purposes. Such models can be used to optimise the structure for maximum efficiency, maximum life, minimum vibration and noise etc. However, model validation and updating is usually a difficult task, not only due to the cost involved during this process, but also due to the fact that a unique and physical model may not be available at the end of the model updating process. The problem is further complicated when the structure has joints and associated nonlinearities. This is a real problem for riveted structures - such as, aircrafts, helicopters, trucks, rails and trailers [1-7] - due to the fact that there may be excessive number of riveted joints for advanced modelling. Furthermore, riveted joints on structures that rely on contact forces to maintain the assembly are not fully modelled yet [1-3]. But there are some practical approaches about riveted joints, especially for the purpose of fatigue life and stress analyses [1-6]. Bisagni [1] dealt with experimental and numerical investigations on the energy absorbing mechanism of a structure fastened by aeronautical rivets. Langrand and others [2-3] dealt with a new numerical methodology to improve the representativeness of the

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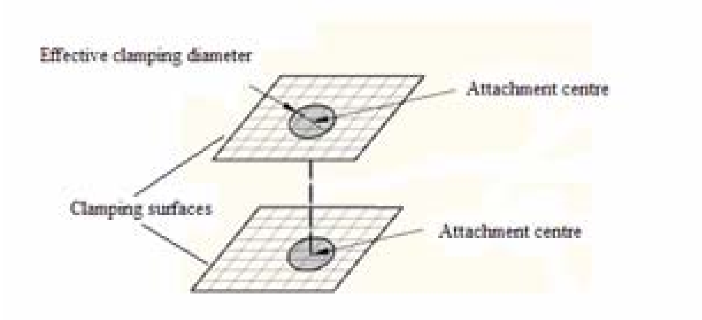
riveted joint modelling for numerical analysis of airframe crashworthiness. Simmons and Schleyer [4] used FE modelling for prediction of the response of riveted and laser-welded stiffened panels to pulse pressure loading. Karaoğlu and Kuralay [5] performed stress analysis of a truck chassis with riveted joints using Finite Element method. Related to modal analysis of riveted structures, Josh and Hau [7] in their study simulated rivets the same way as welds, in which welds are modelled using Point-to-Point Contact (PCM) and Area Contact Method (ACM) and compared modal frequencies and mode shapes with test results. PCM simulates the weld by connecting only one grid point from each side of the welded (riveted) parts with either spring or rigid elements while ACM simulates the weld (rivets) by connecting several grid points from each side of the welded parts with solid, spring or rigid elements.

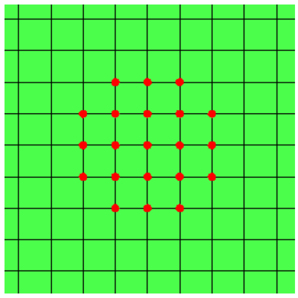
In this paper, a linear FE model of structures with rivets is built by using an effective clamping diameter for a rivet model so as to reflect the stiffening effect. Then the appropriate size of this clamping diameter is determined by correlating predicted modal data corresponding to various clamping diameters with the measured modal data [8, 9]. This is done by first validating the material properties of a structure without any riveted joints. Then, some structures with riveted joints are manufactured, modelled using FE method by assuming that a rivet is effectively clamping the matching surfaces around it within a specified diameter. Then experimental modal analyses are performed to obtain the natural frequencies and mode shapes. The experimentally determined modal data are then used to adjust the effective clamping diameter of the rivets in order to minimize the error between the predicted and the measured natural frequencies and mode shapes. Results show that the procedure explained here can be used to obtain quite representative linear FE models for riveted structures.

2 DEFINITION OF THE PROBLEM AND THE PROPOSED APPROACH

For structures that may contain excessive number of rivets, there is a real need to model the rivets in the structure in an effective way, especially for the determination of the natural frequencies and mode shapes with acceptable accuracy and also to see the effects of the design modifications immediately. However, riveted joints rely on contact forces and in general exhibit non-linear behaviors; hence the “correct” riveted joint model may require complicated non-linear models. However, this is in contrast with the real need in industry due to the serious difficulty of incorporating excessive number of non-linear joint models in structures such as aircrafts and helicopters. Therefore, there is a real need for developing approaches that will be applicable to model structures with excessive number of rivets and that will also yield acceptable accuracy using quite simple, approximate rivet models.

The proposed approach in this study for modelling structures with riveted joints is based on an assumption that each rivet is effectively clamping the matching surfaces within a clamping diameter around the attachment centre. This diameter is also called as “effective clamping diameter” which is illustrated in Figure 1a. In Finite Element (FE) modeling, this assumption can be realized by constraining (joining together) the nodes on matching surfaces of the joint within this diameter [10] as illustrated in Figure 1b.





a) b)

Figure 1: a) FE model of a rivet, b) Joining nodes within the effective clamping diameter

Once the problem is defined as in Figure 1, then the determination of the Effective Clamping Diameter (ECD) for a given rivet configuration becomes the main task. The proposed approach in this paper is to determine the ECD indirectly by utilizing the predicted and measured modal properties of some sample structures assembled using appropriate rivets. The proposed approach is given in Figure 2 as a flow chart. Note that initial validation of the material properties may be necessary if those properties are not known with acceptable accuracy.

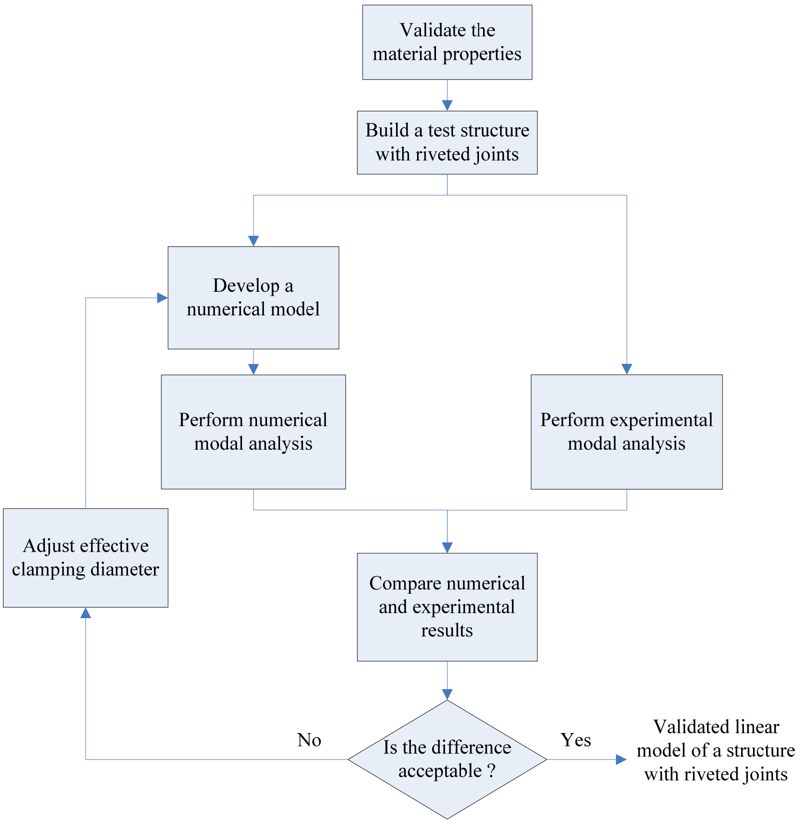
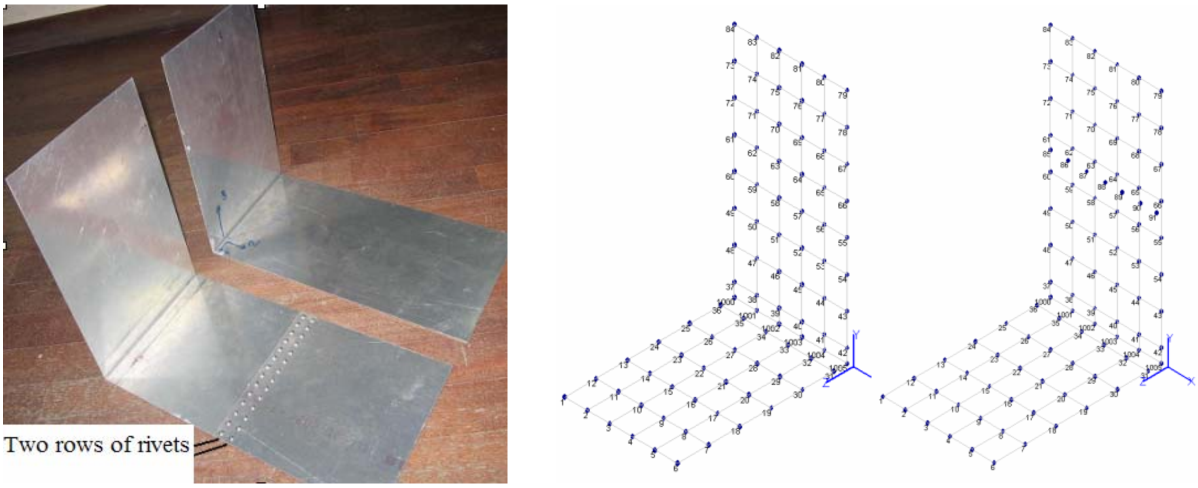


Figure 2: Flowchart for obtaining a validated linear model of a structure with riveted joints

3 CASE STUDIES

3.1 Model Validation of a Riveted L-Plate

For the validation of the rivet model summarized above, two L-shaped plates were manufactured. The plates had identical dimensions and were made of the same material (ALCLAD 2024-T3). However, as can be seen in Figure 3, one of the plate had no rivets at all while the other was made of two parts joined by two rows of rivets. The mass of the plate without any rivets is 459.8 gr and the riveted plate is 499.7 gr, the difference being due to the 28 rivets and the additional material due to overlapping over the riveted region. Here, one of the rivets is 0.824 gr and its diameter is 3.3 mm and its head diameter is 6.4 mm.

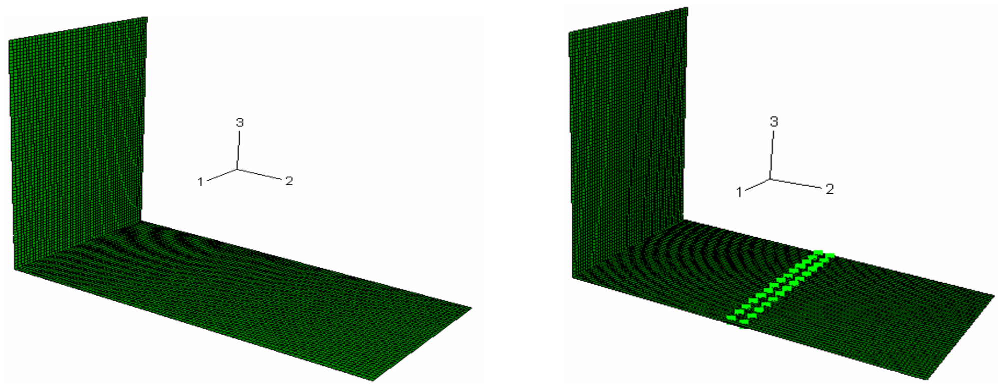


a) b)

Figure 3: a) The riveted plate and the plate without rivets, b) Experimental meshes for plates with and without rivets

Experimental modal analysis was performed on the two plates in free-free conditions using the Frequency Response Functions (FRFs) measured at the nodes depicted in Figure 3b. The FRFs were measured using impact excitation with an instrumented hammer while the responses were recorded using accelerometers. Excitation point was carefuly selected not to miss any mode within the frequency of interest [11] and about 90 FRFs were measured on individual plates. The measured FRFs were processed by ICATS [12] so as to obtain the natural frequencies and mode shapes.

As shown in Figure 4, FE models for individual plates were also developed. Quadrilateral shell elements were used for this purpose and sufficient number of elements were included in the model to avoid any significant discretisation erros within the frequency range of interest.



(a) (b)

Figure 4: a) FE model of the plate without rivets, b) FE model of the riveted plate

The reason for studying the plate without any rivets in this paper is to validate the material properties used in the FE model. This is done by comparing the measured and the predicted natural frequencies and FRFs of the plate without any rivets. Modal Assurance Criteria (MAC) is utilized during the comparisons. The initial material properties used in the FE model are taken from reference [13]. At the end of this exercise, the density and the elastic properties of the material were slightly adjusted so as to match the measured modal properties of the plate. After this adjustment, the predicted and the measured natural frequencies for more than 20 modes agreed quite well (see Table 1). The measured and the predicted FRFs are also compared. A typical example corresponding to point FRF is illustrated in Figure 5a. As can be seen, the FRFs are very close to each other. Small differences in natural frequencies are believed to be due to the mass loading effect [14] of the transducer. Predicted and experimental mode shapes are also compared using Modal Assurance Criteria (MAC) in Figure 5b. It is found that measured and the predicted mode shapes correlated well too.

Table 1: Theoretical and experimental natural frequencies of the plate without rivets

Mode No	Teo. Nat. Freq. [Hz]	Exp. Nat. Freq. [Hz]	Difference [%]
1	10.36	10.28	0.80
2	26.63	26.92	-1.07
3	34.66	34.50	0.48
4	37.09	37.22	-0.35
5	63.03	62.49	0.87
6	83.17	83.77	-0.71
7	104.26	102.50	1.72
8	119.92	118.13	1.52
9	162.06	162.46	-0.25
10	167.87	165.20	1.61
11	173.24	175.29	-1.17
12	185.53	184.10	0.78
13	216.46	214.66	0.84
14	230.89	230.48	0.18
15	240.23	236.63	1.52
16	273.44	268.21	1.95
17	275.55	273.47	0.76
18	322.10	319.72	0.74
19	334.37	327.20	2.19
20	387.13	379.78	1.94
21	394.67	390.14	1.16
22	421.17	414.73	1.55

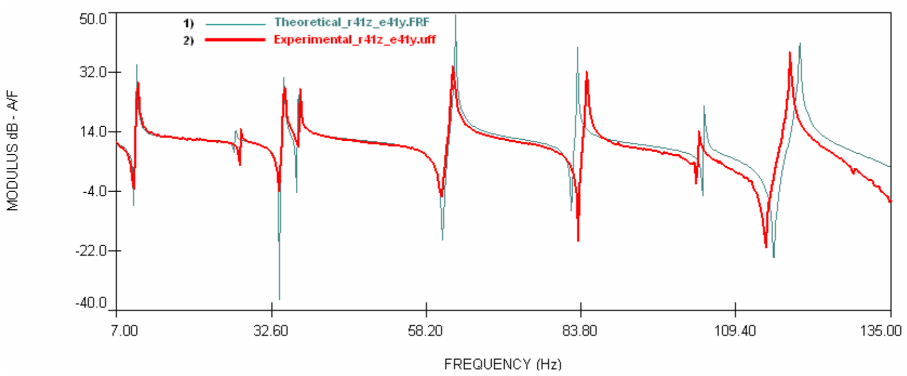


Figure 5a: Comparison of theoretically generated and measured point FRF

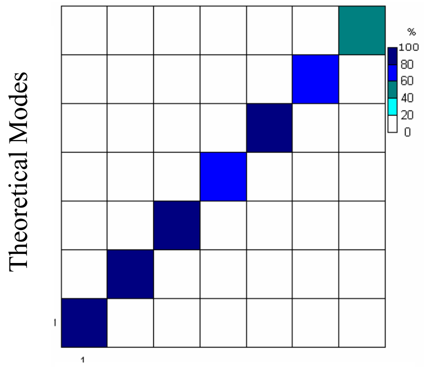


Figure 5b: MAC for the plate without rivets

As mentioned before, the riveted plate was made of the same material as the plate without rivets. Therefore, the validated material properties were also used in the FE model of the riveted plate. As a result, it was safe to assume that any discrepancy between the measured and the predicted behavior of the riveted plate would be due to the errors in modeling the riveted joints. Furthermore, it is aimed in this paper to minimize this error by adjusting the Effective Clamping Diameter (ECD) in Figure 1 according to the approach summarized in Figure 2. To achieve this objective, fully-clamped condition was simulated first, i.e., all the nodes on the matching (overlapping) surfaces of the riveted plate were tied to each other. Then, the analyses were repeated for various values of the effective clamping diameter (D) and the results were compared with measured modal data. The results are summarized in Table 2. It should be noted that the fully-clamped condition sets the upper limit for the predicted natural frequencies. It is also noted that the predicted natural frequencies decrease as the ECD decreases.

Table 2: Theoretical and experimental natural frequencies of the riveted plate

	D=3 mm	D=6 mm	D=20 mm	Fully Clamped	Experimental
Mode No	Natural Frequency [Hz]				
1	10.52	10.46	10.59	10.66	10.39
2	27.42	27.78	29.27	29.13	26.60
3	33.92	34.31	35.13	36.91	33.28
4	37.93	38.08	38.82	38.49	37.42
5	62.76	62.89	63.14	64.02	61.26
6	81.46	82.28	85.00	87.81	79.76
7	107.14	107.25	107.41	107.90	102.85
8	120.41	120.65	120.99	121.33	118.49
9	169.52	170.21	171.07	172.12	167.01
10	174.23	177.33	185.22	183.49	171.40
11	183.19	184.01	194.45	186.88	185.60
12	193.07	193.64	195.08	196.25	192.86
13	215.99	218.31	222.94	231.02	212.98
14	242.62	244.12	250.44	247.84	238.43
15	256.23	258.31	260.61	268.87	262.60
16	269.19	271.71	277.65	281.50	270.10
17	277.62	278.10	278.23	286.61	282.60
18	338.08	339.01	339.96	344.44	328.40
19	346.03	349.83	357.74	364.35	340.20
20	389.48	390.62	390.89	393.08	377.29

The results in Table 2 are processed so as to obtain the percentage difference of the natural frequencies between the measured and the predicted values as a function of ECD and plotted in Figure 6.

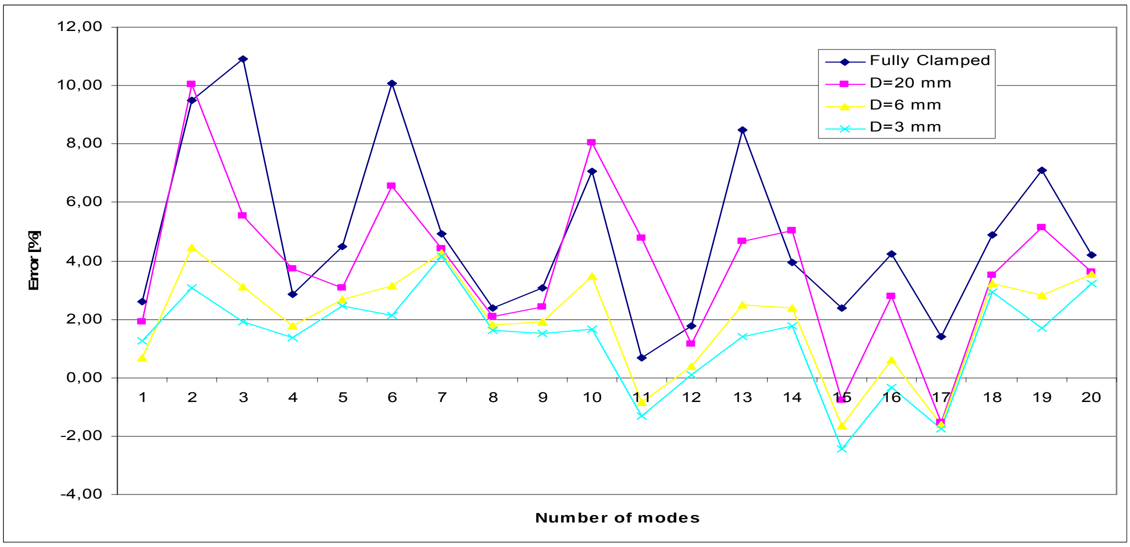


Figure 6: Difference between theoretical and experimental natural frequencies of the riveted plate

Firstly, it seen in Figure 6 that in the case of fully-clamped condition error is the highest, exceeding 10 % for some modes. In the case of the largest ECD (20 mm) the error is also high. It appears that the structure is stiffer than reality in those cases. However, when ECD is low (e.g., 3mm or 6 mm) the FE model represents the real structure very successfully. It should be noted, however, that choosing ECD lower than 3 mm will make the riveted joints over flexible. Therefore, for the particular riveted joints, the optimum ECD was determined to be about 4 mm. Then the modal properties corresponding to this value of ECD were computed and the results are compared to the measured values.

It is shown in Figure 7a that the theoretical and experimental point FRFs agree quite well although the mass loading effect of the transducer is noticeable. The predicted and experimentally identified mode shapes correlate well too as indicated by Modal Assurance Criteria (MAC) in Figure 7b and the visual displays for the first 3 mode shapes in Figure 7c.

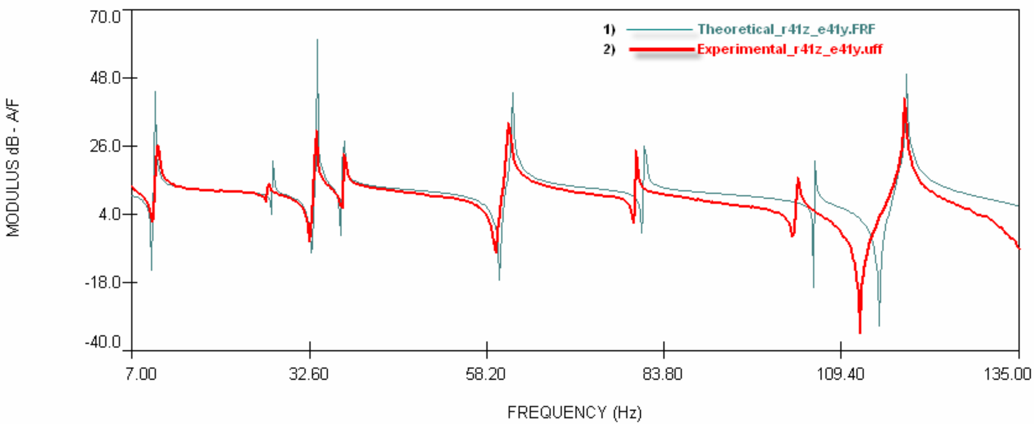


Figure 7a: Comparison of theoretically generated and measured point FRF

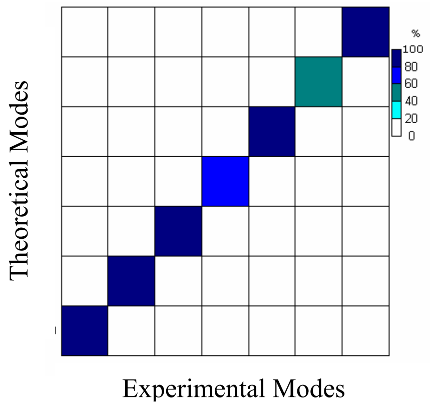


Figure 7b: MAC for the riveted plate

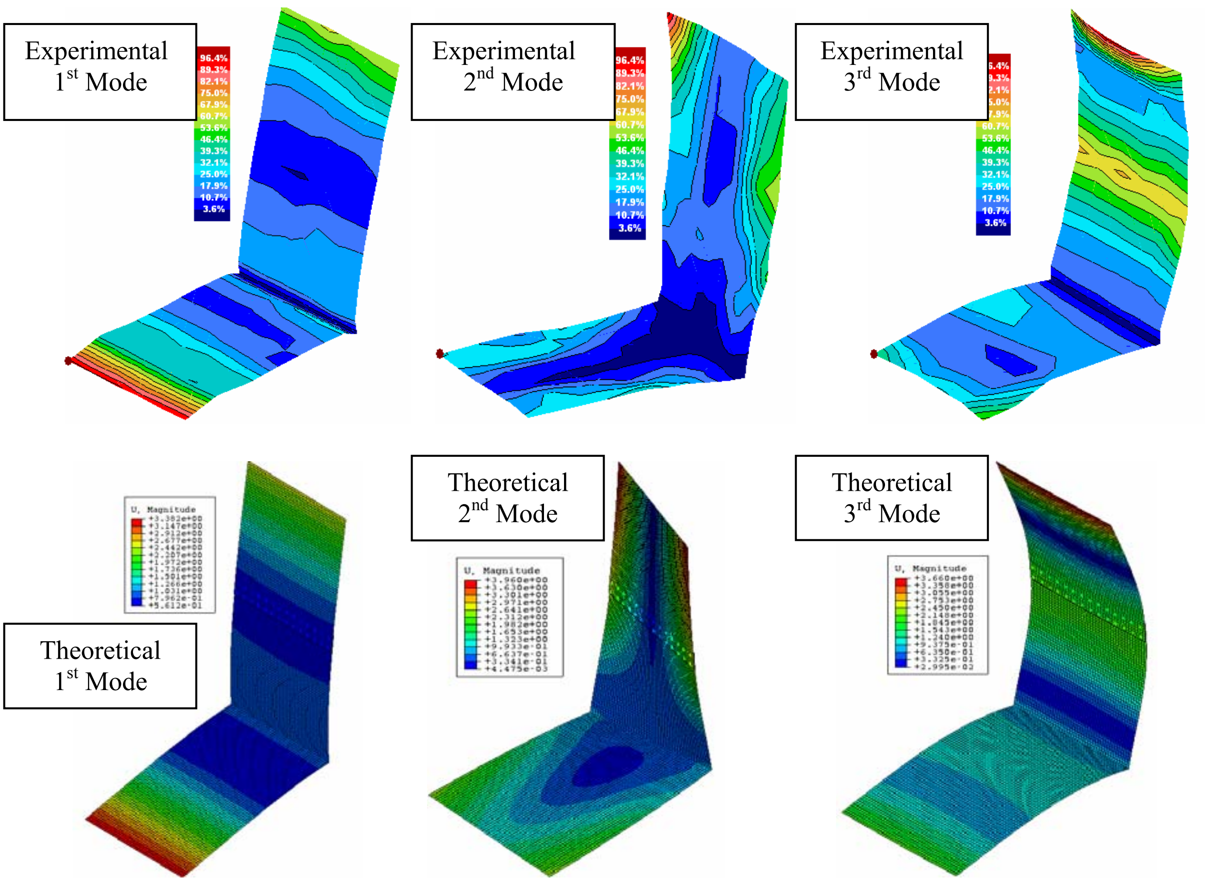


Figure 7c: Comparison of experimental and theoretical mode shapes of the riveted plate

It is worth to state here that the diameter of the rivets used in the test cases was 3.3 mm and the head diameter was 6.4 mm.

3.2 Model Validation of a Riveted Beam

The riveted plate used above was fairly simple in terms of its construction and had only 28 rivets in two rows in a narrow region. It was therefore decided to test the model validation approach using a more complex structure having more riveted regions and a lot of rivets.

The structure tested and validated in this section is called the "riveted beam" and its picture and magnified FE model are given in Figure 8. Riveted beam is about 1.5 kg and comprises 172 rivets in four rows and it is also made of the material (ALCLAD 2024-T3) as

L-plates in the previous section. The dimensions of the rivets used in the construction of this beam were somewhat different than those used in L-plates: the cross sectional and the head diameters were 4.3 mm and 6.4 mm, respectively.

The same approach as in the previous section was followed to model and test this structure. Again, natural frequencies were predicted and they were identified using measured FRFs via experimental modal analysis.

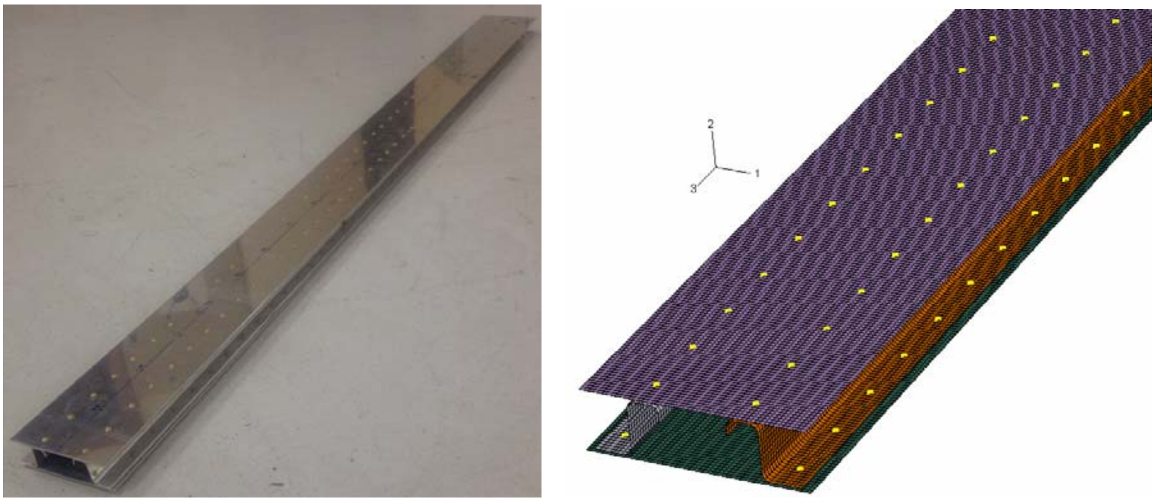


Figure 8: a) Picture of the riveted beam, and b) Magnified FE model of the riveted beam

Again, the FE modal analyses of the riveted beam were performed for different values of ECDs and the results are listed in Table 3. As before and as expected, the results indicate that as the ECD is increased, the predicted natural frequencies also increase. The errors in predicted natural frequencies are also calculated as a function of ECD and the results are presented in Figure 9. The results show that the error between predicted and measured natural frequencies are maximum when the ECD is relatively too large (e.g. 12 mm) or relatively too small (e.g., 4 mm). However, the error is minimum when the ECD is about 6 mm, resulting in errors less than a few percent. It is interesting to note that the optimum value of the ECD is found to about the average of the rivet's cross sectional and the head diameters. Similar observation was made for the L-plate case study.

Table 3: Theoretical and experimental natural frequencies of the riveted beam

	D=4 mm	D=6 mm	D=8 mm	D=9 mm	D=12 mm	Experimental
Mode No	Natural Frequency [Hz]					
1	128.27	128.73	128.99	129.04	129.24	129.840
2	310.43	310.71	310.95	310.96	311.10	307.239
3	327.68	332.29	334.49	335.35	337.37	337.766
4	335.65	358.68	373.64	379.48	393.81	374.428
5	454.83	483.19	502.29	512.57	534.59	487.633
6	544.93	573.33	586.17	590.69	599.20	567.124
7	561.49	579.3	593.43	604.15	626.67	596.873
8	611.34	650.63	673.58	689.91	719.66	645.150
9	704.10	737.56	763.11	774.97	802.47	733.627

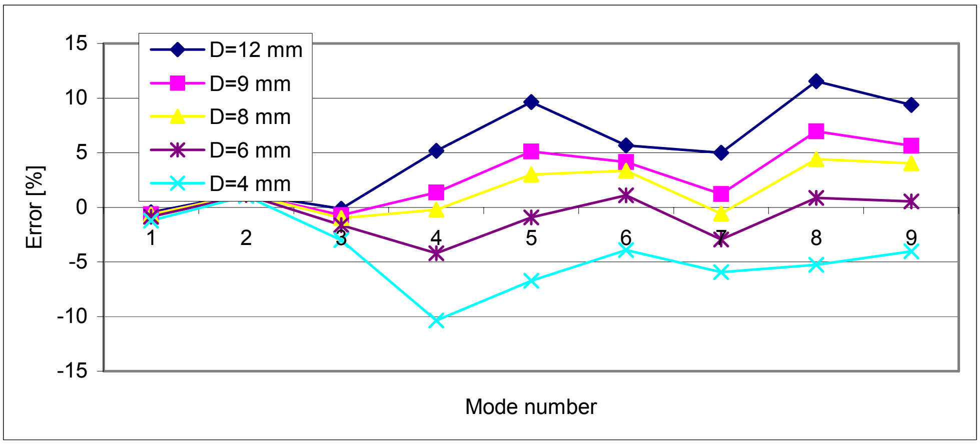


Figure 9: Difference between theoretical and experimental natural frequencies of the riveted beam

The measured FRF and theoretically generated FRF for the case of ECD being 6mm are also compared in Figure 10. It is seen that the correlation is quite good although some natural frequency differences are still obvious. It should also be noted that the FE models did not include any damping, hence the amplitudes of measured and predicted FRFs around natural frequencies are quite different in Figure 10. The modal damping values for individual modes are determined experimentally and, if required, they can be used directly in an FE model described in terms of modal model. Further research seems to be necessary for the damping mechanism if it is to be incorporated in a rivet model.

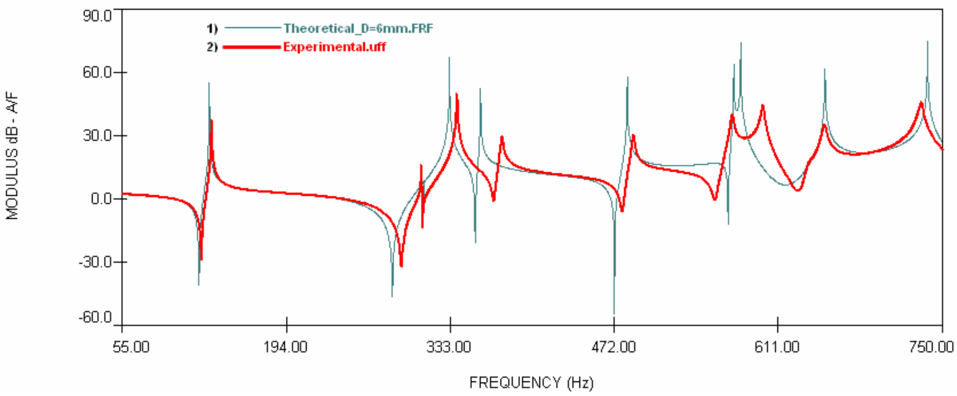


Figure 10: Comparison of measured and theoretically generated FRFs for ECD=6 mm

4 CONCLUDING REMARKS

One of the objectives of this paper was to determine whether an acceptable linear Finite Element (FE) model could be built by adjusting the FE models using the measured modal properties of structures with riveted joints. It has been found that this can be achieved if the objective is to predict the natural frequencies and mode shapes with a few percent accuracy for the lower modes. It has also been found that adjusting the so-called Effective Clamping Diameter (ECD) of the rivet model can be an effective way of tuning the FE model. In the test cases presented in this paper, the optimum value of ECD appears to be very comparable with the cross sectional and head diameter of the rivets. However, this may depend on types of rivets and the methods of construction.

Finally, it is worth stating that incorporating the damping mechanism in riveted joints into theoretical models of structures with huge number of rivets is still a challenging problem.

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