Journal of Mechanical Engineering and Sciences
ISSN (Print): 2289-4659; e-ISSN: 2231-8380
Volume 13, Issue 4, pp. 5780-5790, December 2019

DOI: https://doi.org/10.15282/jmes.13.4.2019.05.0461

The effect of laser stitch welding residual stress on the dynamic behaviour of thin steel structure

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ABSTRACT

Laser stitch welding is one of the most reliable and efficient permanent metal joining processes in the automotive industry, particularly in the manufacturing of a car body-in-white (BIW). It is widely known that this welding process induces the generation of residual stresses that can influence the dynamic behaviour of welded structures. In order to accurately predict the dynamic behaviour of these welded structures, it is important to experimentally understand the influence of residual stress. Therefore, this study aims to addresses the finite element modelling method of thin steel welded structures with and without the influences of residual stress in order to identify its effect towards dynamic behaviour. The finite element models of thin steel welded structures are developed by employing the area contact model (ACM2) format element connector. The accuracy of the finite element models is then compared in terms of natural frequencies and mode shapes with the experimental counterparts. In the experimental part, the dynamic behaviour of the structure is obtained using an impact hammer with free-free boundary conditions and LMS SCADAS is used to process the data. Sensitivity analysis then is used to identify the most influential regions of the residual stress based on the measured data. Results show that, the MAC values of the finite element model with inclusions of residual stress were substantially increased to 0.85 compared to the finite element model without inclusions of residual stress which is 0.55. It can be noted that, the dynamic behaviour of the structure can be accurately predicted by considering the residual stress on the structure in finite element modelling.

Keywords: Laser stitch welding; experimental modal analysis; finite element analysis; dynamic behaviour; residual stress.

INTRODUCTION

In the automotive industry, a typical car body-in-white usually consists of a large number of structural members which are made of thin steel sheets. There are connected together by numerous types of welding. However, in order to fulfil the need to produce a light weight car structure, the application of a laser stitch welding is more preferable [1, 2]. Thousands of joints that are used in a car body-in-white not only form connections between the thin steel sheets but also significantly contribute to the dynamic behaviours of a car [3, 4]. Therefore, a finite element model must be developed in order to predict the dynamic behaviour accurately.

Computerised analysis packages such as the finite element method is found to be more beneficial in predicting the dynamic behaviours of the structure [5]. However, it is difficult and complicated to model the welds itself because of non-linearity effects due to the welding process such as residual stress that are complex and influenced by many uncertain parameters [6–8].

Previous studies reported a few types of element connectors that are widely used to represent welded joints such as rigid body element (RBE), area contact model (ACM2) and weld (CWELD) format [9, 10] There are also several works that are related to the application of shell (CQUAD4) and solid (CHEXA) format [11, 12]. Recent studies reported that the CWELD element connector is more capable of representing a laser spot weld as it has reasonable stiffness and mass of laser spot welds [13]. However, these papers only discussed the modelling of laser spot welds not laser stitch welds, the latter of which have numerous advantages such as smaller flange width, single-side access, much higher strength and low heat distortion. Kuppuswamy et. al. studied modelling techniques for laser welded joints where the accuracy of the model depended on the sheet thickness, and the static and dynamic strength of the joint [14]. Ha et. al. proposed a guideline for accurate finite element modelling of laser welded region for the crash analysis of vehicles [15].

Residual stresses are really significant in welding. It is formed due to the high temperature gradient that is involved during the process. Usually, uncontrolled residual stress may affect the quality of welded structure since it induces shape distortion and reduces fatigue strength [16]. However, it is very difficult to theoretically estimate or experimentally measure such residual stress, unless the unstressed configuration is first measured in the latter case, which is very rare in reality. Works related to the influence of residual stress on the dynamic behaviours of structure were reported in [16, 17].

This paper is aims to identify the accuracy of the predicted dynamic behaviour of the thin steel welded structure without considering residual stress and with considering residual stress on the finite element models in the light of experimental data. Sensitivity analysis is used in this research as a tool to identify the most influential regions due to the residual stress.

EXPERIMENTAL MODAL ANALYSIS OF A LASER STITCH WELDED STRUCTURE

A simplified model of a car body-in-white structure as shown in Figure 1 has been used in this study. The structure is made of cold rolled mild steel sheet with 1.5 mm thickness, 560 mm length and 110 mm wide. Experimental factors such as frequency bandwidth, suspension orientation, excitation method and the number of accelerometers need to be considered for the finite element analysis [18].

In order to replicate the free-free boundary conditions, four sets of nylon strings and springs are used to hang the structure from the clamps (Figure 2). These nylon strings and springs are used to suspend the structure because it has a very minimal effect (lightly damped) on the test structure and can be neglected [19]. The frequency bandwidth of interest of the test structure is 0 Hz to 700 Hz.

In this test, the dynamic behaviours of the test structure are obtained using the impact hammer and roving accelerometers as shown in Figure 3. An impact hammer is used to excite the structure with one fixed reference accelerometer. Meanwhile, the remaining three accelerometers are roved around to completely measure the response. It is important to arrange accelerometers systematically in order to avoid any mass loading issues to the test structure during the experimental process [20, 21]. Finally, the LMS SCADAS system is used to interpret the load and signal produced by the test structure.

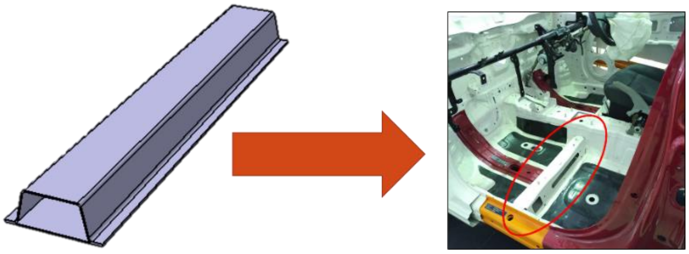


Figure 1. Simplified model of a car body-in-white.

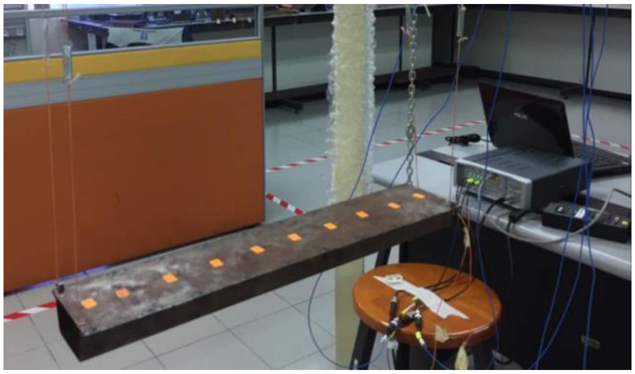


Figure 2. Experimental setup of the laser stitch welded structure.

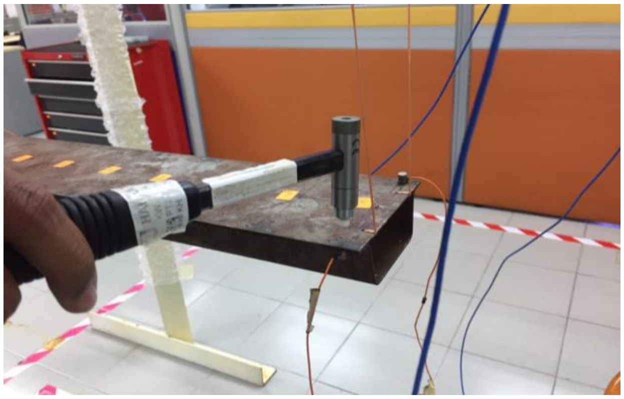


Figure 3. Impact hammer in experiment.

FINITE ELEMENT MODELLING OF A LASER STITCH WELDED STRUCTURE

In this work, the structure is designed as hat-plate structure connected by laser stitch welds as shown in Figure 3 in order to replicate the common substructure of a car body-in-white.

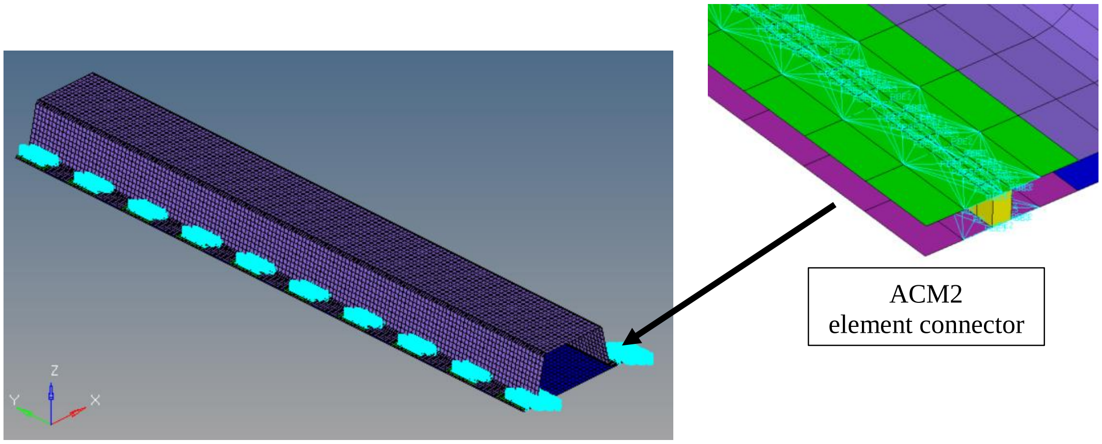


Figure 4. The finite element model of a laser stitch welded structure.

The hat-plate structures were discretising into shell elements with 13090 elements and 13348 nodes. Meanwhile, the modelling of the laser stitch welds in the hat-plate structure was prepared using ACM2 element since it is capable of representing laser stitch welds.

The dynamic behaviours of the FE model of hat-plate structure were predicted using the MSC NASTRAN SOL 103 by solving the Equation. (1).

$$(\mathbf{K_e} - \omega^2\mathbf{M})\phi = 0 \tag{1}$$

where, K_e and M are the elastic stiffness and mass matrices respectively, while ω and ϕ represent natural frequency and eigenvector respectively. In this analysis, the modes of interest were the first ten elastic modes starting from 0 to 1000 Hz while the material properties of the model are based on nominal value of mild steel: Young’s modulus: 211 GPa, Poisson’s ratio: 0.28 and Density: 7860 kg/mm^3 [22].

Representation of ACM2 Element Connectors as Laser Stitch Welds

The finite element model of laser stitch welds was developed by employing a connector known as ACM2 as proposed by Heiserer et. al. [23]. This model uses a brick element as nugget and is connected to the upper and lower surfaces by the RBE3 element at the welded position. Moreover, the RBE3 elements are used to distribute the applied loads in order to remove the problem of high local stiffness when a rigid link is applied. This element model also allows non-congruent meshes to be employed in which the welds can be located anywhere in the model.

In the finite element model, 118 ACM2 element connectors are used to represent the 20 laser stitch welds. The material properties of the welds are assumed to be almost similar to the nominal value of the structures. The geometry of the laser stitch welds however is varied depending on the representation of the real structure. The average measurement for the thickness and length of the laser stitch welds are 1.4 – 1.6 mm and 19 – 22 mm respectively.

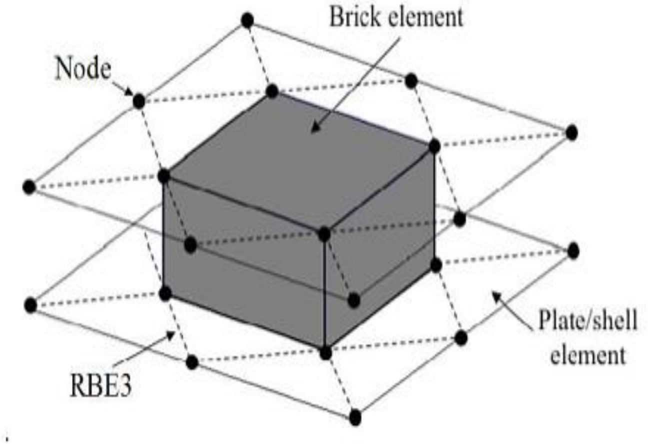


Figure 4. ACM2 element connector [23].

Finite Element Modelling of Residual Stress

The influence of residual stress on dynamic behaviour can be understood by developing the prediction model of structure. In the absence of a completed unstressed configuration data in this study, the residual stress of laser stitch welding is assumed.

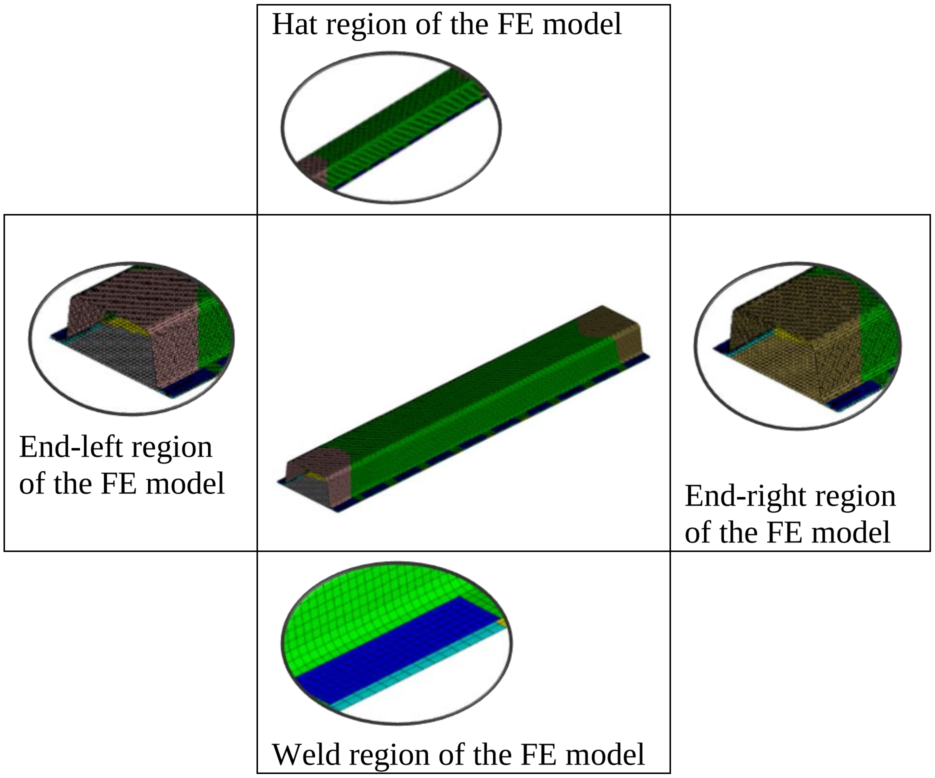


Figure 5. Finite element model with residual stress regions.

In this research, the residual stresses were distinguished into four different regions namely; hat region, end-right region, end-left region and weld region as shown in Figure 5. From the observation and engineering judgement, these regions were suspected to have significant contribution on the dynamic behaviour of the structure due to the residual stress. However, it should be noted these four regions were only based on engineering point on view, therefore the sensitivity analysis was carried out to identify the most influential region. Basically, sensitivity analysis is the study to find out how the uncertainty in the output of a finite element model can be apportioned to different sources of uncertainty in its inputs [28, 29]. It can be a valuable tool in structural dynamic analysis where the dynamic behaviour such as natural frequencies are known through experiment modal analysis can be a benchmark to the predicted results in order to amend the uncertainties such as residual stress. Based on the sensitivity analysis as shown in Figure 6, it has been found that the most influential residual stress region is on hat.

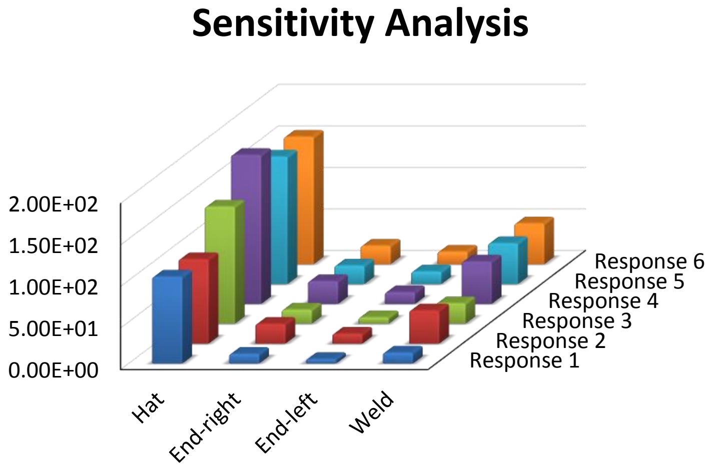


Figure 6. Sensitivity analysis chart.

The dynamic behaviours of a laser stitch welded structure with the inclusion of residual stress can be obtained by solving the Equation. (2).

$$\left(\mathbf{K}_{\boldsymbol{e}}+\mathbf{K}_{\mathbf{g}}-\omega^{2}\mathbf{M}\right)\phi=0 \tag{2}$$

where, K_e and K_g are elastic stiffness and geometric stiffness matrices respectively, while M is the mass matrices. Further, ω and ϕ represent natural frequency and eigenvector respectively.

MODAL ASSURANCE CRITERION (MAC)

The dynamic behaviour obtained such as natural frequencies and mode shapes from the initial finite element model and residual based finite element model are compared with experimental counterparts in order to validate the accuracy of the finite element models. However, to evaluate the accuracy of mode shapes in particular, it is required to pair mode shapes between experimental and finite element modes correctly. The method such as modal assurance criterion (MAC) is usually used to quantify the mode shapes as to indicate the level of accuracy of the modes between finite element models and experimental model [24–26]. Generally, MAC is used to calculate experimental modes and finite element modes in matrix form, which can be calculated from Equation. (3).

$$\mathrm{MAC} = \boldsymbol{\Phi}_m \boldsymbol{\Phi}_a = \frac{\left|\boldsymbol{\Phi}_m^T \boldsymbol{\Phi}_a\right|^2}{(\boldsymbol{\Phi}_a^T \boldsymbol{\Phi}_a)(\boldsymbol{\Phi}_m^T \boldsymbol{\Phi}_m)} \quad (3)$$

Where $\boldsymbol{\Phi}_a$ is finite element mode shapes and $\boldsymbol{\Phi}_m$ is experimental mode shapes. The MAC value is a scalar constant that ranges between 0 and 1. The value 0 indicates that it is not in good correlation while value 1 indicates that it is in good correlation between two sets of vectors [27].

RESULTS AND DISCUSSION

In this study, the dynamic behaviour of laser stitch welded structures which are natural frequencies and mode shape were obtained numerically. The results were then compared with the experimental data to confirm the accuracy of the models. The finite element models of the welded structure were jointed using the ACM2 element connector. Results obtained using the above mentioned methods were showed in Table 1.

The measured natural frequencies and mode shapes are used for the comparisons made on the initial finite element and residual stress finite element counterparts. It can be seen that in Table 1, the total error of the first six modes of initial FE is 22.54 percent (Column III) and the average MAC value is above 0.55 (Column IV). The MAC values result reveals that, without considering residual stresses, the mode shapes of FE are not in good agreement with the measured data. These results suggest that it is mandatory to include the residual stress to the initial finite element model as presented in sensitivity analysis since the initial model does not physically represent the behaviours of the laser stitch welded structure. Previous studies have revealed that welded structures are more tends to experience residual stress that trapped into the structure causes by welding process correlation [30, 31]. These suggest that the dynamic behaviour of the structure may influenced by the trapped residual stress.

When modifications were made with the inclusion of residual stress on the finite element model, the discrepancy between the natural frequencies of the first six modes were reduced from 22.54 to 13.34 percent (Column VI). Furthermore, since the average MAC value is above 0.85 (Column VII), the result reveals that the mode shapes have changed when residual stresses are considered. In other words, the mode shapes of residual stress of the finite element model were shown to be in good agreement with the measured data. The results in Table 2 and Table 3 shows the mode shapes of the finite element models without and without inclusion of residual stress respectively. Its shows that mode shape in Table 3 are in good agreement with experimental counterpart compared with the mode shapes in Table 2 as agreed in the MAC values shows in Table 1. Previous studies have suggested that the predicted mode shapes with MAC values above 0.70 can be acceptance as in good correlation [5].

In this work, it was found that residual stress due to the welding process is one of the important parameters that need to be considered in developing the finite element model. It is essential to accurately estimate the residual stress of the laser stitch welding because it is an influential parameter that affects the dynamic behaviours of the thin steel structure, particularly the mode shapes [15].

Table 1. Comparison between measured and predicted natural frequencies of laser stitch welded structure.

Mode	**I Experiment (Hz)**	**II Initial FE (Hz)**	**III Error (%) [I-II/I]**	**IV MAC**	**V Residual stress FE (Hz)**	**VI Error (%) [I-V/I]**	**VII MAC**
1	521.52	519.48	0.39	0.90	521.48	0.01	0.93
2	591.17	563.16	4.74	0.92	572.51	3.16	0.92
3	595.44	569.08	4.43	0.55	574.26	3.56	0.88
4	674.67	642.06	4.83	0.76	654.54	2.98	0.94
5	681.61	658.85	3.34	0.72	678.31	0.48	0.85
6	694.64	661.19	4.81	0.61	672.74	3.15	0.87
Total Error			**22.54**			**13.34**	

Table 2. Comparison of mode shapes between measured and initial FE model.

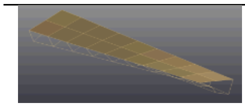
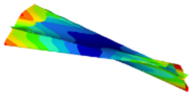
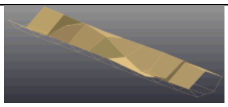
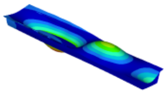
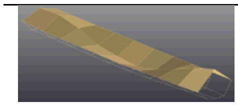
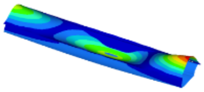
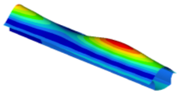
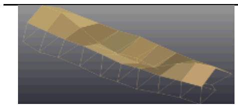
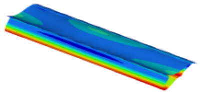
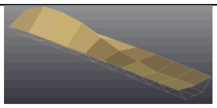
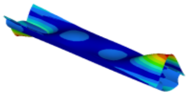
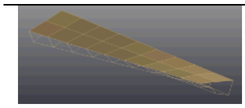
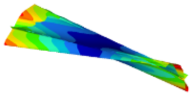
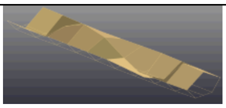
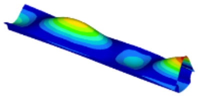
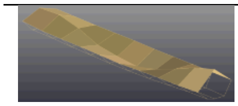
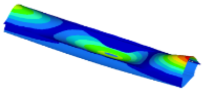
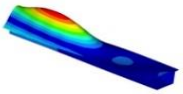
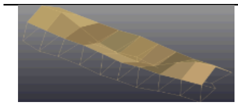
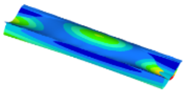
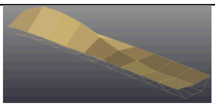
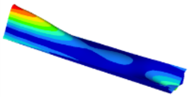
Measured mode shape	**FE mode shape**	**Measured mode shape**	**FE mode shape**
 Mode 1	 Mode 1	 Mode 4	 Mode 4
 Mode 2	 Mode 2	 Mode 5	 Mode 5
 Mode 3	 Mode 3	 Mode 6	 Mode 6

Table 3. Comparison of mode shapes between measured and residual stress FE model.

Measured mode shape	FE mode shape	Measured mode shape	FE mode shape
 Mode 1	 Mode 1	 Mode 4	 Mode 4
 Mode 2	 Mode 2	 Mode 5	 Mode 5
 Mode 3	 Mode 3	 Mode 6	 Mode 6

CONCLUSIONS

This work presents the experimental and predictions of the influence of laser stitch welding residual stress on the dynamic behaviours of thin steel structures. The experimental data were carefully measured in order to correlate with the predicted model. Accuracy of the correlation between predicted and measured dynamic behaviours such as the natural frequencies and mode shapes of the laser stitch welded structure make up the prime objective of the research. The total error of the natural frequencies of the structure has been reduced from 22.54 to 13.34 percent and the mode shapes of the structure shows in good agreement in which the MAC values of the structure improve from average of above 0.55 to the above 0.85 when inclusion of the residual stress is considered in finite element modelling. The improvement of the relative error and the MAC values of the dynamic behaviours of the thin steel structure suggests that the inclusion of residual stress induced by the welding process needs to be considered in developing the finite element model as it represents the original behaviours of structure. A continuous study in improving the finite element model of laser stitch welded structure is recommended especially in applications of finite element model updating.

ACKNOWLEDGEMENTS

The research has been funded by the Malaysian Ministry of Higher Education (MOHE) and Research Management Institute (RMI) of Universiti Teknologi MARA (UiTM) for Research Grant with the file number 600-IRMI/PERDANA 5/3/BESTARI (073/2018). Besides, the authors would like to express thankfulness to the members of the Structural Dynamics Analysis and Validation (SDAV) UiTM for their technical assistance and laboratory facilities.

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