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Dynamic Behaviour Estimation of Laser Stitch Welded Structure

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Abstract. An accurate analytical model of the physical assembled structure is predominantly importance for engineers and designers to be used in predicting the dynamic behaviour of the structure. Powerful tools such as finite element analysis (FEA) and experimental modal analysis (EMA) can be used to determine the dynamic behaviour of the assembled structure. The assembled structure such as automotive structure is normally joined by a number of jointing types such as spot welds, bolts, and adhesive. However due to advancement of the jointing method, the laser jointing method have been significantly used in the automotive industries. However, it is challenging and cumbersome to accurately model a structure that are assembled by a combination of complex types of joints such as laser stitch welds. This is because stitch welds have been discovered as joining method that tends to present the local effect such as structure geometrical irregularities, heat affected zone (HAZ) on the welded areas and also the residual stress that occurs from the laser welding process. In addition, it is challenging to only rely on the prediction of the dynamic behaviour using FE method because predicted results are often found inconsistent with the experimental data. The inconsistencies of the results due to invalid assumptions of laser stitch welds are the significant motivation to the main goal of this paper by investigating the accuracy of the finite element model of the laser stitch welded structure. In this paper, the prediction of the dynamic behaviour of the structure are merely to address the local effects due to the laser stitch welds such as geometrical irregularities, HAZ and residual stress that influence the initial prediction of the laser stitch welded structure by producing highly accurate prediction model as close to experimental data. The inclusion of the local effects to the initial FE model are performed in the sensitivity analysis to identify the most sensitive parameters of the laser stitch welded structure. The FE model updating method was employed with corresponding to the measured result for reconciliation purpose. The results revealed that the inclusion of the local effects due to the welding process can significantly improve the prediction of the dynamic behaviour of the laser stitch welded structure and the implementation of the sensitivity analysis was successful in correcting the source of error by improving the correlation of the predicted results with experimental counterpart.

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INTRODUCTION

Laser stitch welding has become more popular in automotive industries such as to assemble the car body in white (BiW) and components because of it is highly productive in comparison to the traditional welding methods such as metal inert gas welding (MIG), tungsten inert gas welding (TIG), and resistance spot welding. This is because laser stitch welding offers many advantages such as low heat input, low distortion, deep penetration, and ease of automation and is being used today in many different industries [1]. Moreover, the contact-free work by laser stitch welding produces high welding speeds and achieves an economical advantage [2]. In fact, laser welding has become one of the first choices in welding methods considered in modern manufacturing. The advantages in metallurgy, versatility and flexibility are considered and make laser stitch welding a much better alternative that other welding methods.

Even though the process of laser stitch welds to assemble structure is simple, fast and easy to handle. However, the structural modal testing needs to perform in order to investigate the dynamic behaviour of the assembled structure due to the dynamic loading. Meanwhile, there are many studies remain to be interested in process of simulation, weld strength and safety factor particularly in the laser stitch weld joint and it should be noted that the understanding towards the dynamic behaviour of the assembled laser stitch welded structure are also needs significant attention [3]–[5].

Theoretically, dynamic behaviour of a structure usually described in terms of two components namely; natural frequencies and mode shapes. It is important to investigate the natural frequencies of the structure using experimental modal analysis, (also known as modal testing) to identify the resonance frequencies of the assembled structure due to driven frequency. Meanwhile, the resonance occurs whenever the natural frequency of the structure coincides with the driven frequency. Furthermore, resonance can cause damage to the structure due to excessive deflection. Meanwhile the mode shapes are acts as specific patterns that reflect the behaviour of the assembled structure due to the structural resonance.

The advancement of computer technologies such as processing power and data storage capacity allows the engineer to predict the dynamic behaviour of the structures efficiently. In structural dynamics, finite element method is frequently used to predict the dynamic behaviour of the structure by modelling the geometry in the finite element software. Meanwhile, the results obtained from experimental modal analysis is used as a benchmark for validation process by performing the reconciliation process to the finite element models of the assembled structure.

Generally, the finite element method is able to solve large and complex problems with complex geometries, loads and boundary conditions [6]–[8]. However, to model the laser stitch welded structure using finite element method is very difficult, challenging and time consuming due to the involvement of local effects and uncertainties induced to the structure during the welding process such as geometrical irregularities, heat affected zone (HAZ) and residual stress [2]. These uncertainties may affect the dynamic behaviour of the structure and thus, finite element model need to be carefully constructed. Previous study by Rani and Husain, reported that there are few types of element connectors that are widely used to represent laser welded joints such as Rigid Body Element (RBE2), Area Contact Model (ACM2) and spot weld element such as CWELD format [9], [10]. However, Azam indicates that the most appropriate element connector to represent as laser stitch welds is ACM2 [11]. There are few studies that emphasis about the important of inclusion the welding effects in finite element modelling in order to improve the accuracy of prediction results [12]–[14]. Bernardini et al. [15] stated that it is important to produce highly accurate geometry of structures prior to perform the finite element analysis. On top of that, Lozano et al. [16] improved the prediction model by increasing the size of heat affected zones on structure. Meanwhile, Vourna et al. [17] highlight the tendencies of structure to experience residual stresses after undergo manufacturing process. However, it is found that the prediction results are frequently not in good agreement with experimental counterparts due to the invalid assumptions made in the finite element modelling [18]. One way to refine, correct or update the finite element model through which the dynamic behaviour of a structure is predicted using model updating methods [19].

The subject of model updating methods has received much attention from many researchers [20]–[22]. Model updating methods are a systematic procedure of reconciling a finite element model in the light of measured results [23]. Therefore, this paper is intended to investigate the accuracy of the finite element model of laser stitch welded structure by addressing the problem of local effects due to the laser stitch welds such as geometrical irregularities, HAZ and residual stress that influence the initial prediction of the structure to produce highly accurate prediction model of the assembled structure. To obtain the acceptable model of the assembled structure, the finite element model was then employed in the model updating method with the measured data were as a benchmark data for reconciliation purpose in order to improve the accuracy of predicted results.

MODAL TESTING OF THE WELDED STRUCTURE

In this research, experimental modal analysis (EMA) was performed on the laser stitch welded structure in order to identify the modal parameters of the structure such as natural frequencies and mode shapes. Prior to perform the experimental work, several factors in experiment such as number and the location of measuring points, the selection of the excitation points and the range frequency of interest were firstly identified, through the initial prediction of the dynamic behaviour of the structure. The laser stitch welded structure as illustrated in Figure 1 was under investigation. As shown in Figure 1, the structure was designed in a simplified form so as to replicate a common pillar, cross and side members of a typical car body in white (BiW). Initially, the structures consist of two different components which are hat shaped and flat plate shaped and were connected together using laser stitch welding joining method. The structure contains 20 laser stitch welds with 23 mm nominal length and 1 mm thickness on both flange areas. The components of structure were made from cold rolled mild steel sheets and the components has dimensions of 564 mm in length, 110 mm in width and 45 mm in height.

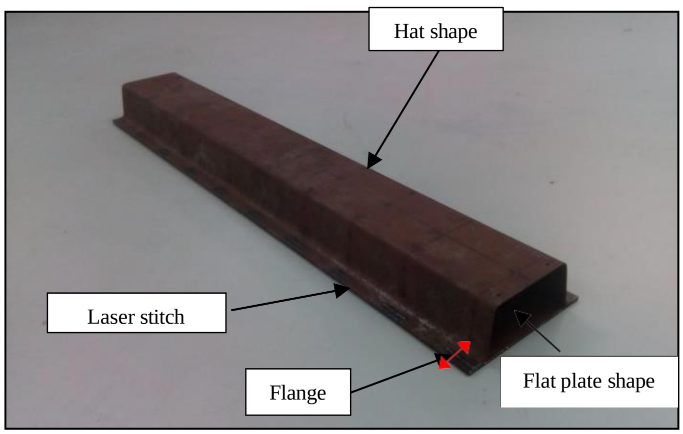


FIGURE 1. Laser stitch welded structure

MODEL TESTING METHODOLOGY

Generally, the dynamic behaviour of structures in experimental modal analysis are obtained by analysing the relationship of the excitation (force) given at particular node with the structural response in another node. The structural response is usually in terms of acceleration, velocity and displacement. These signals from excitation and responses were then transformed via Fourier transform into frequency domain known as frequency response function (FRF). In other words, the experimental modal analysis is a method to measuring the FRF's of a physical structure in order to identify its dynamic behaviour such as natural frequencies and mode shapes. However, in performing experimental work of laser stitch welded structure, few conditions need to be considered for instance, the linearity check on the structure. The purpose of this test is to identify the homogeneity of the structure due to the involvement of the welding process. The non-linearity in the structure can be identified using shaker test under low-level vibration. The non-linearity can be identified if the peak of FRFs is shifted when the level of input energy is increased [24].

Secondly, it is important to include adequate degree of freedom and vibration modes within the range frequency of interest. Likewise, that unnecessary data needed to be excluded from the measurement to characterise the physical structure experimentally. A proper choice of response degree of freedom is important to visualise the mode shape of the structure accurately. Furthermore, erroneous in selecting the range frequency of interest may cause the experimental to miss mode of interest. This work was including the range of 0 to 700 Hz of frequency interest with six mode shapes where available to obtained.

EXCITATION TECHNIQUE FOR THE EXPERIMENTAL WORK

The selection of excitation method plays important role in producing a good experimental modal analysis data. Basically, there are two different methods to excite the structure commonly known as impact testing and electro-dynamic shaker. The electro-dynamic shaker (as shown in figure 2) usually used by physically mounted to the structure through the force transducer where the excitation force was transmitted via stinger rod and formed an attachment between the structure. This type of arrangement was then creating the possibility of altering the modal parameters since the attachment between stinger rod and force transducer was only creating a mass loading effects to the structure. Moreover, the shaker test set-up took longer time and more suitable to be used for a large structure such as complete car body in white because it was producing high input force to excite the structure.

Impact hammer is another excitation method in the experiment. By using impact hammer excitation method, there is no need to connect the impact device to the test structure since the force transducer is attached to its head. In this situation, the mass loading effect can directly be avoided. This method was considered as the simplest method as it required less hardware with no burdensome set-up and provided shorter measurement time.

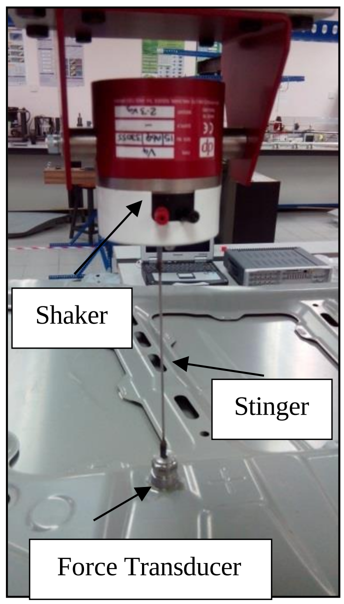


FIGURE 2. Electro-dynamic shaker

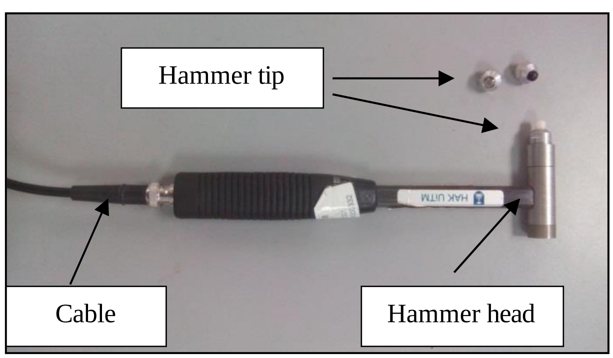


FIGURE 3. Impact hammer

In impact hammer method (as shown in figure 3), the excitation of force is known as impulse, is used to excite a desired range of frequency. This desired range of frequency is depending on the properties of the hammer tips. Furthermore, the stiffness of the surface structure also will affect the shape of the impulse, and then influences the range of frequency. However, it is impossible to change the stiffness of the test structure; thus, the frequency range is controlled by varying the stiffness of the hammer tips. It can be concluded that, the stiffer the hammer tips, the higher the frequency range covered by the impact. It is important to obtain high quality FRFs data. Thus, in this research, impact hammer with the plastic tip was selected as shown in Figure 4. Figure 5 shows the excitation energy for impact hammer used in this experiment. The figure shows that the excitation used were enough to cover the frequency of interest. Furthermore, during the experiment, the averaging factor in the excitation needed to be considered. The number of averages in the experiment for this research is set up to 10 times excitation.

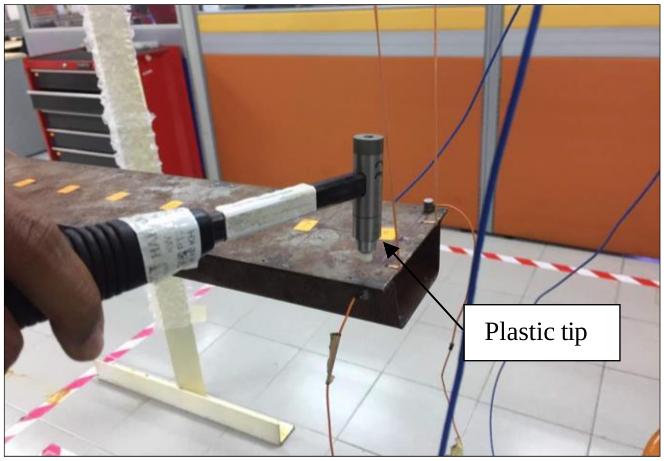


FIGURE 4. Impact hammer in experimental modal analysis (EMA)

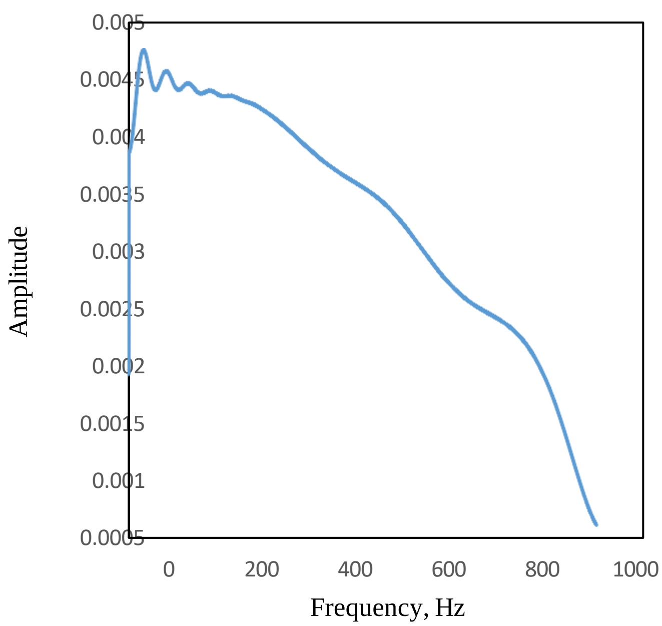


FIGURE 5. Excitation energy of impact hammer in experimental process

VIBRATION RESPONSE TRANSDUCER

In the experimental work, the mechanism used to measure the input excitation is known as force transducer while the output vibration response is measured by accelerometers (Figure 6). For this work, the piezoelectric crystal force transducer was used to measure the input excitation force signal. The force transducer was allocated at the Bruel and Kjaer (B&K) impact hammer with the sensitivity of 11.73 mV/N and connected by the sensor cable. The vibration responses of structure generally are accelerations, velocities and displacements. It can be measured at one or more nodes. The system output of vibration response normally being measured by motion transducer knows as accelerometer. Most of the accelerometers used in experiment were piezoelectric accelerometer [25]. However, it is important to consider some factors when applying the accelerometer on the structure. Firstly, there are various mounting methods of accelerometers and the advantages and disadvantages of each technique need to be considered. Figure 7 shows six mounting methods and their effects on the performance of an accelerometer.

In this research, adhesive mount was considered as the best mounting technique as it provided the easiest attachment. Adhesive mount such as wax perform well for temporary installations and by considering it size, it can be mounted on curved and complex structures. Secondly, the weight of accelerometer also plays a crucial part on the measured response especially for a structure made from thin metal sheet. If the structures experience an additional weight from the accelerometer, then it will certainly change the modal parameter of structure particularly in natural frequency. This is because the coefficients of the differential equations are not constant and has change with respect to the time.

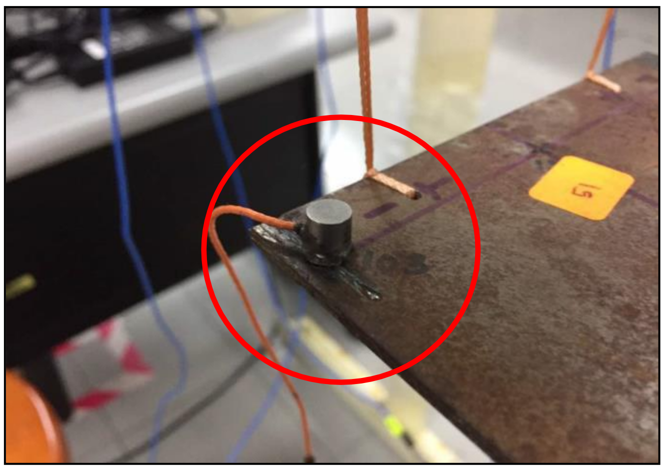


FIGURE 6. Accelerometer used in experimental modal analysis (EMA)

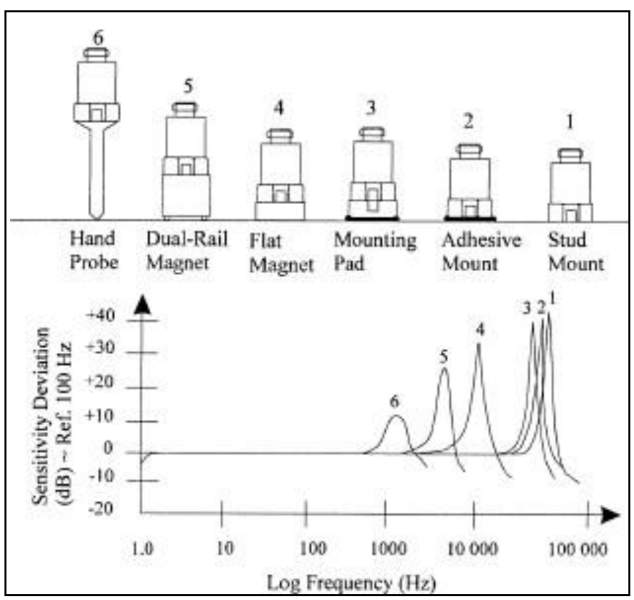


FIGURE 7. Different types of accelerometer mounting method [25]

There were three set of accelerometers used in which two of them were roving over the structure and another one was fixed to the point of the impact hammer. The information of accelerometers used in the experimental work is highlight in Table 1.

TABLE 1. Information of the impact hammer and accelerometers

Apparatus	Manufacturer	Sensitivity	Direction
Accelerometer 1 (Fixed)	Dytran	10.23 mV/g	Z-direction
Accelerometer 2	Dytran	10.54 mV/g	X- & Z-direction
Accelerometer 3	Dytran	9.63 mV/g	X- & Z-direction

METHOD OF SUPPORT AND SELECTION OF MEASURING NODES

Method of support such as free-free boundary conditions are known as the most popular supported condition in an investigation of modal parameters [26]. These support conditions are more preferred because they produce a very minimal effect on the modal parameters. Free-free boundary conditions requires the test structure to floating in the air with no connection to the ground and producing rigid body modes at zero frequency. In order to simulate free- free boundary conditions, the test structure can be suspended with soft elastic cords or soft spring. The test structure can also be placed on a very soft material such as sponge or rubber pad. These types of design will make the structure constrained and the rigid body modes would not be at zero frequency. However, the rigid body frequencies will be much lower than the elastic mode. Therefore, the effect of the support can be neglected. Previous study by Wolf [27] reported the rule of thumb to simulate the free-free boundary conditions is by designing the support condition that are the highest frequency of rigid body modes that must be 1/10 to the lowest elastic mode. In this work, the laser stitch welded structure was hung using soft spring and string. Prior to conducting the experimental work, it is important to determine the excitation node and measurement nodes of the structure. The number and position of measuring nodes must be carefully select to cover the measuring frequencies and the mode shapes of the structure. Basically, the number of measuring nodes and excitation node depend on the range of frequency interest, number of transducer and available test time. All these criteria are studied from predicted the mode shapes. It also depends on the number of transducer and available test time. In order to reduce a possibility to losing any modes, the measuring nodes must be spread equally throughout the test structure.

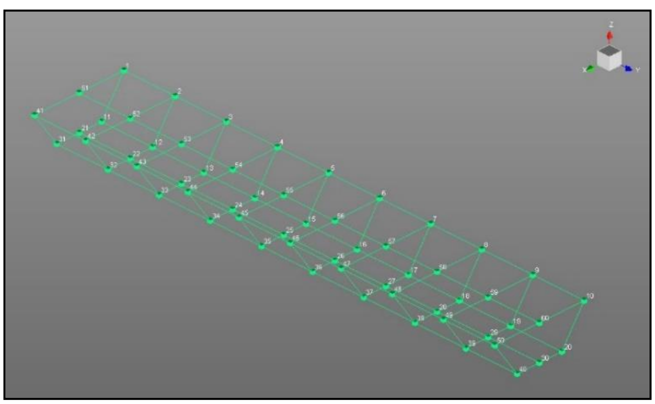


FIGURE 8. Measuring points of laser stitch welded structure

The accuracy of the test result completely depended on the way the accelerometer was installed. If too many accelerometers were installed, then there were chances for the structure experience increasing of mass and stiffness that can cause alter the response due to the mass loading issue of the structure. Hence, the accelerometer used in the experiment should not exceed 1/10 of the weight of the structure to be measured [28]. In this experiment, there were 60 nodes of measurement and the node positions were located as shown in Figure 8. In order to determine both bending and torsion modes, accelerometers were roved in two directions (i.e., the X- and Z- directions) because one of the actual modes apparently could not get by measure only in one direction (i.e., Z- directions).

FINITE ELEMENT MODELLING

The finite element model of laser stitch welded structure was used as a case study to illustrate the proposed updating procedure. In the pre-processing stage of the finite element modelling, the MSC PATRAN was used to develop the finite element model. The structure was modelled using CQUAD4 elements and the model was meshed into 5 mm meshing size (Figure 9) based on the suitability of the meshes size obtained from mesh convergence test results. The Area Contact Model (ACM) element connectors then were used to represent as laser stitch welds and to connect the hat shape plate and flat shape plate subcomponents as recommended from previous studies [29]. The nominal material properties of mild steel were used in the finite element modelling is shown in Table 2 [11].

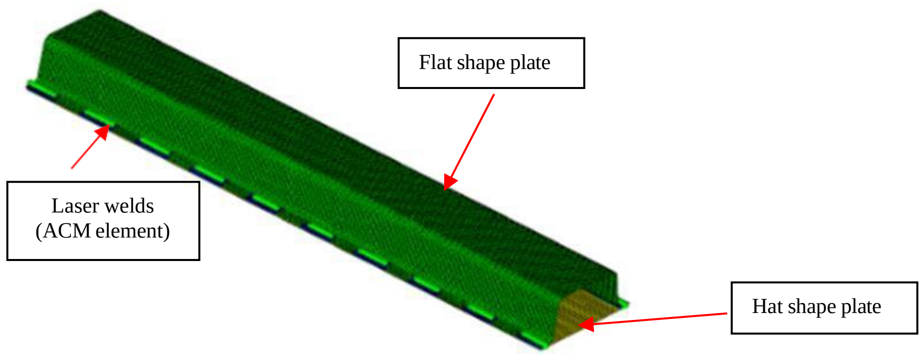


FIGURE 9. FE model of laser stitch welded structure

In this research, normal mode analysis was obtained using SOL 103 of MSC NASTRAN to identify the natural frequencies and mode shapes of the finite element model. The generalised of the equation of motion used to discretise the system into a finite element model, also known as 2nd order differential equation is given as

$$\mathbf{M}\ddot{x}(t) + \mathbf{C}\dot{x}(t) + \mathbf{K}x(t) = f(t) \quad (1)$$

where **M**, **C** and **K** are symmetric matrices of mass, damping and stiffness. Meanwhile $\ddot{x}$, $\dot{x}$ and x represent the vector of accelerations, velocities and displacement respectively and f(t) is vector of external forces. The structure that been used in this research were considered having light damping and the effect of damping can be theoretically neglected and as a result, for the undamped free vibration analysis, the equation (1) can be simplified as

$$\mathbf{M}\ddot{x}(t) + \mathbf{K}x(t) = 0 \quad (2)$$

The equation (2) can be solved by assuming the harmonic solution in the form of

$$x = \phi sin\omega t \quad (3)$$

where ω and ϕ are the mode shape and natural frequency of the system. If the differentiation of the assumed harmonic solution is performed and substituted in equation (2), the equation of motion yields and simplified to the following

$$(\mathbf{K} - \omega^2\mathbf{M})\ \phi = 0 \quad (4)$$

The natural frequencies and mode shapes of the laser spot welded structure can be predicted by solving the equation (4) using finite element commercial software such as MSC NASTRAN.

In order to quantified the mode shapes of finite element model with experimental data counterpart, the modal assurance criterion (MAC) are use. It is necessary to pair modes between finite element and experimental modal analysis correctly to identified the degree of correlation between that pairing mode shapes vector. The MAC is calculated as

$$MAC = (\phi_{ema}\phi_{fe}) = \frac{|\phi_{ema}^T\phi_{fe}|^2}{(\phi_{fe}^T\phi_{fe})(\phi_{ema}^T\phi_{ema})}\ x\ 100 \quad (5)$$

where Φ_m are finite element mode shapes and Φ_a 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 perfect correlation between two sets of vectors. However, for the complex jointed structures such as laser stitch weld are necessary to have acceptable range of mode shapes correlation between 0.7 to 1.0 [30]. Table 2 shows the initial prediction of natural frequencies for the area contact model 2 (ACM2) based FE model. In this table, the computed natural frequencies of FE model are compared with the experimental natural frequencies (EMA) to evaluate the accuracy of the FE model. The total relative error has found to be 33.97 %. The results revealed that, there were no mode swapping issue in the predicted results of the ACM2 based FE model. Therefore, ACM2 based FE model may suitable to be used in FE model updating to reduce the model discrepancies against experimental counterpart. Table 2 also shows that, ACM2 based FE model has manage to predict the natural frequencies of the structure consistently in the range of frequency of interest. This is because the ACM2 element connectors can provide reasonable stiffness to the FE model of the structure in the range of the frequency of interest.

ACM2 element connector has several advantages comparing to others element connectors that available in the commercial FE software, such as it contains the upgraded version of the brick element consisting the weighted average constraint element or RBE3. The RBE3 elements were employed to distribute applied load onto nodes in which it was removing the infinite local stiffness when only applying the RBE2 element [31]. Besides, ACM2 element connectors ignores the needs of congruent meshes. Consequently, the laser stitch welds can be employed anywhere in the model regardless of the surface condition.

TABLE 2. Comparison natural frequencies and mode shapes of experimental (EMA) and initial FE model

I Mode	II EMA (Hz)	III ACM2 FE Model (Hz)	IV Error (%) (II-III)/II	V MAC
1	521.52	519.33	0.42	0.90
2	591.17	556.07	5.94	0.92
3	595.44	565.89	4.96	0.55
4	674.67	618.15	8.38	0.76
5	681.61	628.49	7.79	0.72
6	694.64	649.62	6.48	0.61
Total Error			**33.97**	

However, based on the MAC results in the Table 2, it has been noted that initial ACM2 based FE model was not perfectly predict the mode shapes of the laser stitch welded structure particularly in mode 3, mode 4, mode 5 and mode 6 where MAC of the stated mode shapes were below 0.9. This is because in modelling FE model with involvement of weld joints is always difficult due to of the existence of many local effects that induced during welding process. Local effects such as geometrical irregularities, heat affected zone and residual stress are difficult to be incorporated in FE modelling and thus might influence the result of predicted dynamic behaviour. Therefore, to successfully predict the dynamic behaviour of structure, the improvement of the initial ACM2 based FE model was continuing by addressing all the local effects determined that may influence the results.

This work is crucial in minimising the discrepancies of the results which are natural frequencies and mode shapes of the structure before performing model updating.

FE MODELLING USING COORDINATE MEASURING MACHINE (CMM)

In this subsection, the procedure to improving the initial ACM2 based FE model of the laser stitch welded structure are presented. In order to minimising the effect of geometrical irregularities, the improvised version of the FE model was done by remeasuring the geometry of the structure using coordinate measuring machine (CMM) as shown in Figure 10. Based on the technical observation and engineering judgements on the structure profile, it was found that the laser stitch welded structure was slightly offset and deformed (Figure 11). Therefore, this step is crucial in order to construct more precise and accurate geometry of the FE model.

FIGURE 10. Coordinate measurement machine (CMM)

FIGURE 11. Geometrical irregularities of the structure

From Table 3, it can be seen that the relative total error in natural frequencies of the latest ACM2 based FE model (CMM) were not much different with the initial ACM2 based FE model with the difference being around 1 %. However, the great achievement in this work is the dynamic behaviour of the structure has been well predicted compared to initial FE model. It can be supported by the result shown in Table 3 particularly on mode shape 3. Previously, the mode shape 3 of the initial ACM2 based FE model was not correlated well with the measured data where the MAC is 0.55. The mode shape of the latest ACM2 based FE model is in good agreement with measured data with the MAC is 0.90. It clearly shows the improvement in predictions on dynamic behaviour of laser stitch welded structure between these two models particularly on mode shape 3, therefore, it is vital to use a precise geometry for FE modelling by systematically obtaining the profile of the structure. However, FE model using CMM technique still cannot accurately predict the dynamic behaviour of the laser stitch welded structure in mode 4, mode 5 and mode

6. Therefore, next stage of FE modelling needs to be done in which by maximising the inclusion of heat affected zones (HAZ).

TABLE 3. Comparison natural frequencies of experiment, initial ACM2 and ACM2 based FE model (CMM)

I Mode	II Exp (Hz)	III Initial ACM2 FE Model (Hz)	IV Error (%) (II-III)/II	V MAC	VI ACM2 FE Model (CMM) (Hz)	VII Error (%) (II-VI)/II	VIII MAC
1	521.52	519.33	0.42	0.90	500.97	3.94	0.93
2	591.17	556.07	5.94	0.92	564.73	4.47	0.93
3	595.44	565.89	4.96	**0.55**	568.56	4.51	**0.90**
4	674.67	618.15	8.38	0.76	624.77	7.40	0.80
5	681.61	628.49	7.79	0.72	632.09	7.27	0.76
6	694.64	649.62	6.48	0.61	660.08	4.97	0.68
	Total Error		33.97			**32.56**	

FE MODELLING OF HEAT AFFECTED ZONE (HAZ)

This subsection explains the procedures of the ACM2 based FE model of laser stitch welded structure with the inclusion of HAZs. This work was carried out to minimising the effect of local effect due to HAZs. The development of the FE model has been done by maximising the areas of the HAZs due to the welding process. The HAZs has been found to be one of the uncertain parameters and need to be considered in developing the predicted model. Initially, the FE model with small size HAZs were used in the investigation of the dynamic behaviour of laser stitch welded structure. The size of HAZs were set to be 20 % bigger than the weld size [10]. The elements used in modelling of HAZs containing their own properties in which may be beneficial in adjusting the models in model updating process. Then, the size of HAZs were increased to 70 % bigger than the weld size (as shown in Figure 13). Basically, the HAZs is the area of base material which is not melted and has had its material properties altered by welding operation. The exact size of the HAZs has become unknown since it depends on the amount of the heat input during welding process. The size of the HAZs has been determined based on engineering observation and judgements carried out in order to replicate the actual structure. Figure 12 shows the HAZs of the laser stitch welded structure. Table 4, gives the comparison of the predicted dynamic behaviour of laser stitch welded structure between ACM2 based FE model (CMM) and ACM2 based FE model with increased HAZs. The discrepancies of the natural frequencies for all six modes are reduced significantly, with the highest error recorded is 6.68 %. Meanwhile, based on the MAC results, the mode shapes of mode 4, 5 and 6 still are not correlated well with experiment data. However, this step is crucial since the area of HAZs on the welds are relatively difficult to be estimated. The region of HAZs are always different to each other. This is owing to the fact that the parent material immediately next to a weld have been heat-treated by the welding process and the welding can change the local hardness and modify the grain structure of the parent material with unknown size [32].

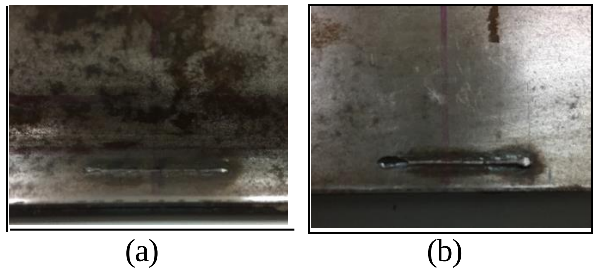
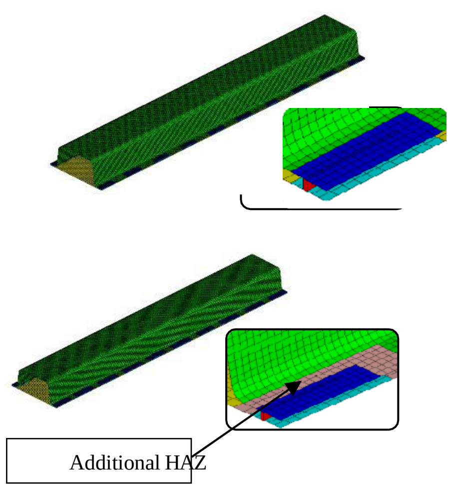


FIGURE 12. Welded area with HAZ on (a) hat component, (b) flat plate component

TABLE 4. Comparison natural frequencies of experiment, initial ACM2 and ACM2 based FE model (CMM)

I Mode	II Experiment (Hz)	III ACM2 FE Model (CMM) (Hz)	IV Error (%) (II-III)/II	V MAC	VI ACM2 FE Model (HAZ) (Hz)	VII Error (%) (II-VI)/II	VIII MAC
1	521.52	500.97	3.94	0.93	503.51	3.45	0.95
2	591.17	564.73	4.47	0.93	569.27	3.70	0.94
3	595.44	568.56	4.51	0.90	571.93	3.95	0.90
4	674.67	624.77	7.40	0.80	629.59	6.68	0.81
5	681.61	632.09	7.27	0.76	636.39	6.63	0.76
6	694.64	660.08	4.97	0.68	665.67	4.17	0.68
	Total Error		32.56			**28.59**	



FE model with HAZs size 20 % bigger than joint size.

FE model with HAZs size 70 % bigger than joint size.

FIGURE 13. Heat affected Zone (HAZ) of laser weld

FE MODELLING WITH RESIDUAL STRESS EFFECT

Previously, the HAZs area of laser stitch welds have been increased to improve the predicted result of the structure. It has been found that the relative error of natural frequencies was reduced with 4 % and mode shapes in mode 1, mode 2 and mode 3 were excellently correlated with experiment data. However, the result also reveals inabilities of the FE model in obtaining the higher modes such as in mode 4, mode 5 and mode 6 which the MAC still below 0.9. Generally, at the higher frequency range, the dynamic behaviour of a jointed structure is in complex mode behaviour. As agreed with previous studies, modelling weld joints is always difficult because it involved the existence of many local effects particularly induced during welding process [33]. Therefore, the residual stresses have been introduced to the FE model of laser stitch welded structure. Based on the observation carried out on the influences of the welding process to the structure, the residual stresses have been introduced on the regions in laser stitch welded structure such as hat component, HAZs, end-right and end-left of the structure.

The initial value of the residual stresses has been set to 1.00 and the corresponding of the regions parameter with actual structure will be found in the model updating results. By addressing all the possible existing local effects due to the welding process, the FE model with ACM2 element connectors represent as laser stitch welds can be used to predict the dynamic behaviour of laser stitch welded structure. However, results in Table 4 show that the total relative error of the FE model is 28.59 %. Therefore, in order to reduce the discrepancies of the FE model with the experimental data, the FE model updating via iterative method need to be performed by systematically manipulating input properties of the laser stitch welded structure. It is necessary to tune some influential parameters to ensure that the FE model can closely represent the actual dynamic behaviour of the structure.

FINITE ELEMENT MODEL UPDATING

As stated in previous subsection, the ACM2 based FE model with inclusion of local effects such as geometrical irregularities, HAZs and residual stress has better capabilities to represent as laser stitch welded structure. However, the computed predicted results tabulated in Table 4 show significant error when compared with experimental modal analysis results where the total relative error is 28.59 %. The error may occur from invalid approximation made about properties of the initial model. Therefore, to improve the accuracy of predicted results, the uncertain parameters of ACM2 based FE model need to be altered. In this study, a systematic model updating method (FE model updating via iterative method) was applied to the FE model to improve the accuracy of the predicted natural frequencies. FE model updating is an approach to improve the correlation of finite element model and the actual structure by correcting the invalid assumptions of the model to an acceptable level of accuracy. In the structural dynamics, the structural response are often eigen-solutions related to such as natural frequencies and mode shapes. In this research, natural frequencies are employed as objective response. Therefore, the optimised objective function is formulated in terms of the residuals between analytical and measured natural frequencies and can be expressed as,

$$J = \sum_{i=1}^{n} W_i \left(\frac{\lambda_i^{\text{fe}}}{\lambda_i^{\text{exp}}} - 1 \right)^2 \quad (6)$$

where, λ_i^{exp} is the i-th experimental eigenvalue and λ_i^{fe} is the i-th predicted eigenvalue from the finite element model and n is the number of eigenvalues involved in the updating procedure.

Basically, the FE model updating via iterative method was processed based on sensitivity analysis. The objective from the sensitivity analysis is to identify the sensitive parameters that contribute to the error by listing the potential parameters. It should be noted that parameters involved in the updating process must be selected properly. This is because only parameters that are sensitive to the natural frequencies are only considered as updated parameters. The observation and engineering judgements were successfully carried out by underlying the right candidates of the updating parameters before performing the sensitivity analysis [34]. The sensitivity analysis of the of the laser stitch welded structure is shown in Figure 14.

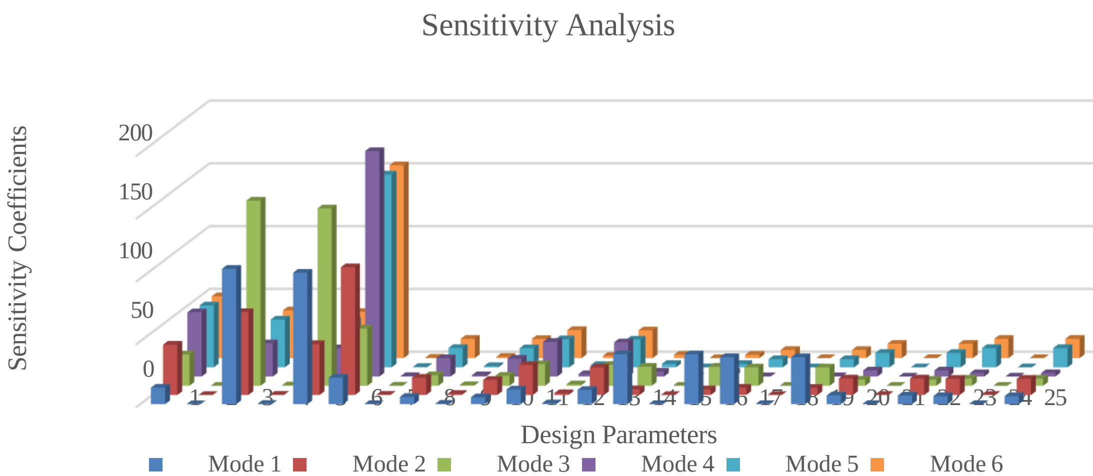


FIGURE 14. Sensitivity analysis chart

From Figure 14, it can be summarised that the natural frequencies were most sensitive to the changes of six parameters which are Young's modulus of laser stitch welds (1), Young's modulus of hat shapes (3) and flat plate components (6), residual stress on hat component (5), and finally Young's modulus of HAZ on hat (5) and flat plate component (11). The sensitivity analysis obtained revealed that the presence of the HAZs, residual stress and the stiffness of laser stitch welds have significantly contributed to the error between FE and experiment results. The results also revealed that the stiffness of the flat plate component contributed to the erroneous on the higher frequency which are mode 4, mode 5 and mode 6. Therefore, all the sensitive parameters need to be updated in order to reduce the discrepancies of modal parameters between finite element and experimental counterpart. Based on the observation and engineering judgements, the sensitive parameters were allowed to be updated in a limited reasonable range only in order to preserve the physical meaning of the updated parameters. The initial value of the sensitive parameters such as Young's modulus (E) of the hat-plate components was set to 210 GPa. Based on the handbook of material, the Young's modulus of mild steel was only varying in range between 180 GPa to 220 GPa [35]. Therefore, the Young's modulus of hat shape and flat plate components were allowed to vary on the range of fraction between 0.9 to 1.048. Meanwhile, the initial Young's modulus of laser stitch weld was set to 320 GPa, it also has a variation to be updated in a range of 0.9 to 1.048 in order to preserve the physical meaning of updated parameter [34]. Moreover, the initial Young's modulus of HAZs on hat shape and flat plate components were set to 270 GPa, it also has a variation to be updated in a range of 0.9 to 1.048. Since the residual stresses (RS) are difficult to be measure, therefore, the residual stress effect on hat component was allowed to vary in a range of 0.1 to 2.5.

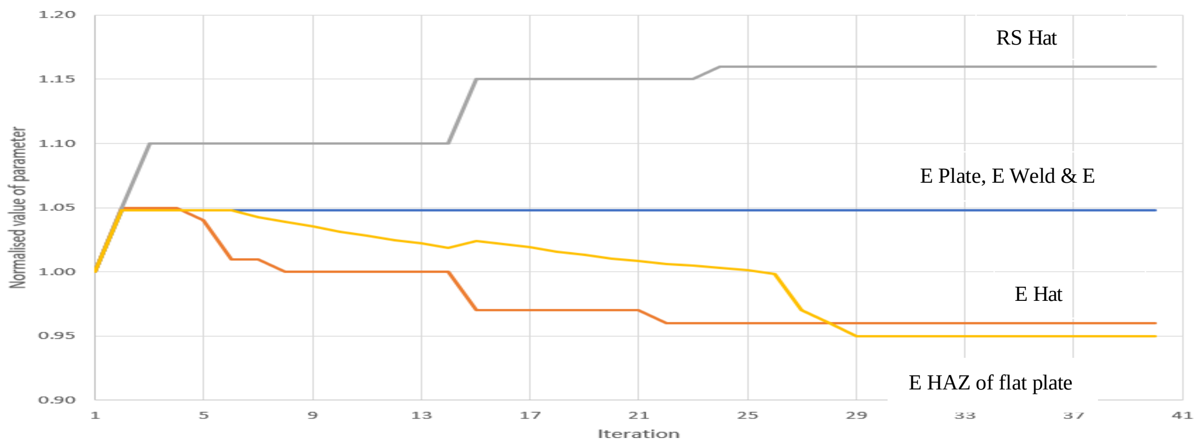


FIGURE 15. Updated parameters convergence

The minimisation process of the error in the initial FE model is calculated by solving objective function on Equation 3.8. The iteration is stopped until the convergence of the objective function is accomplished and the last iteration is used as an updated value in the FE modelling. In this work, model updating was carried out with the benchmark of the first six measured natural frequencies of the laser stitch welded structure. As depicted in Figure 15, the updating procedure has converged until 40 iterations. The updated parameters are presented in Table 5. Table 6 tabulates the results of the updated natural frequencies in comparison with the initial natural frequencies. From the table, impressive achievement of individual and total error had been acquired after considering the sensitive parameters as the updating parameters. The total error of the initial natural frequencies has been dropped from 28.59 % to 6.35 %.

TABLE 5. Updated parameters values

Parameter	Initial value	Updated value
E, Hat component	210 GPa	200 GPa
RS, Hat component	1.0	1.16
E, Flat plate component	210 GPa	220 GPa
E, laser stitch weld	320 GPa	335 GPa
E, HAZ on hat component	270 GPa	283 GPa
E, HAZ on flat plate component	270 GPa	268 GPa

Based on the finite element model updating results, ACM2 element connector has shown a very great potential in representing as laser stitch weld. The massive improvement in the correlation of predicted results with measured data has suggested that ACM2 element connectors has capability to represent as laser stitch welds in the structure. The huge improvement of the results also corresponds from the efficiency of the sensitivity analysis which proven to be a powerful tool for identifying the source of error and correcting updated parameters. Individually, the 1st, 2nd, 3rd and 6th modes have shown very great improvement with the natural frequency was almost in perfect correlation with the errors has been dropped to below than 1 %. Meanwhile, the 4th and 5th modes have shown better improvement with errors of 2.5 %. However, only mode shapes in the 1st, 2nd, and 3rd modes were perfectly correlate with experimental mode shapes with MAC almost to 1.0. On the other hand, the MAC for the mode shapes in 4th, 5th and 6th modes were above 0.6. Despite the errors of natural frequencies and mode shapes in the 4th, 5th and 6th modes of the FE model have been significantly reduced, the modes remain to be the major contributor to the error in the updated FE model. This is because at the higher mode, mode shapes of the structure will behave complexly, and the mode shapes will involve with local deformations. Therefore, it was difficult to obtain highly accurate mode shapes on 4th, 5th, and 6th. These limitations have been seen as the major problems and challenging in the predicting dynamic behaviour of laser stitch welded structure. In order to overcome these problems, in-depth investigation on the involvement of other local effects due to the welding process, such as defect and contacting area can be carried out in the future.

TABLE 6. Comparison natural frequencies of experiment and updated ACM2 based FE model

I Mode	II Experiment (Hz)	III Updated ACM2 Model (Hz)	IV Error (%) II-III	V MAC
1	521.518	521.77	0.05	0.98
2	591.170	590.22	0.16	0.98
3	595.437	598.84	0.57	0.97
4	674.665	657.69	2.52	0.85
5	694.635	664.49	2.51	0.77
6	726.469	690.84	0.55	0.69
	Total Error		**6.35**	

CONCLUSIONS

This paper has presented experimental modal analysis and finite element modelling procedures for the laser stitch welded structure to identified modal parameters of the structure such as natural frequencies and mode shapes. Comparison of the initial prediction of the structure with experimental data counterpart has reveals that there is high inaccuracy of the initial FE model. This is because experimental study has revealed that the local effects from the welding process such as geometrical irregularities, heat affected zones and residual stresses have contribute to the large discrepancies on the natural frequencies and mode shapes of the predicted model, especially at the higher modes. Producing reliable experimental data also play major role in the development of finite element model. This is because the experimental data is used to correcting the initial finite element model. However, without considering the local effects of the structure in finite element modelling, an accurate model with high accuracy is impossible to be obtained especially for the laser stitch welded structure. Therefore, it is very crucial to address these local effects in order to minimise the discrepancies of the FE model before performing model updating method. Furthermore, the study

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Dynamic Behaviour Estimation of Laser Stitch Welded Structure

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Abstract

An accurate analytical model of the physical assembled structure is predominantly importance for engineers and designers to be used in predicting the dynamic behaviour of the structure. Powerful tools such as finite element analysis (FEA) and experimental modal analysis (EMA) can be used to determine the dynamic behaviour of the assembled structure. The assembled structure such as automotive structure is normally joined by a number of jointing types such as spot welds, bolts, and adhesive. However due to advancement of the jointing method, the laser jointing method have been significantly used in the automotive industries. However, it is challenging and cumbersome to accurately model a structure that are assembled by a combination of complex types of joints such as laser stitch welds. This is because stitch welds have been discovered as joining method that tends to present the local effect such as structure geometrical irregularities, heat affected zone (HAZ) on the welded areas and also the residual stress that occurs from the laser welding process. In addition, it is challenging to only rely on the prediction of the dynamic behaviour using FE method because predicted results are often found inconsistent with the experimental data. The inconsistencies of the results due to invalid assumptions of laser stitch welds are the significant motivation to the main goal of this paper by investigating the accuracy of the finite element model of the laser stitch welded structure. In this paper, the prediction of the dynamic behaviour of the structure are merely to address the local effects due to the laser stitch welds such as geometrical irregularities, HAZ and residual stress that influence the initial prediction of the laser stitch welded structure by producing highly accurate prediction model as close to experimental data. The inclusion of the local effects to the initial FE model are performed in the sensitivity analysis to identify the most sensitive parameters of the laser stitch welded structure. The FE model updating method was employed with corresponding to the measured result for reconciliation purpose. The results revealed that the inclusion of the local effects due to the welding process can significantly improve the prediction of the dynamic behaviour of the laser stitch welded structure and the implementation of the sensitivity analysis was successful in correcting the source of error by improving the correlation of the predicted results with experimental counterpart.

SciVal Topics

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