RESEARCH ARTICLE

SAMRIDDHI Volume 14, Issue 3, 2022 Print ISSN: 2229-7111 Online ISSN: 2454-5767

Modal Analysis of Diagonally Hat Stiffened Square Plate to Distinguish Spot Weld Rupture

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Abstract

Abstract-In the field of vibration engineering, Modal analysis is popularly used for structural analysis to determine its modal parameters like modal frequencies, mode shapes, and damping ratio. Hat stiffened structures are inherently used in all three kinds of transportation industries like automobiles, aviation, and marine. The change in the modal parameter values indicates the disintegration happened within the structure. In this paper, a square plate is stiffened with a hat channel along its one of the diagonal by applying spot welds on both flanges. A finite element model of this structure is solved using ANSYS software to obtain modal parameters. The results obtained from the finite element analysis (FEA) are validated using the Experimental Modal analysis (EMA) technique. Extreme welds on one side of the stiffener are separated from the plate, and new modal parameters are obtained using FE analysis and verified by EMA. The modal parameters assessment of both cases has shown a relation of weld partition with the intrinsic properties of the structure.

Keywords: Experimental modal analysis, Finite element analysis, Hat stiffened plate.

SAMRIDDHI : A Journal of Physical Sciences, Engineering and Technology (2022); DOI: 10.18090/samriddhi.v14i03.06

Introduction

Today's industrial environment leads to pursuing increasingly lightweight strategies for most of the structural components. Among these, several structures resemble a hat stiffened plate. Hat stiffener is usually formed in sections and is generally welded, riveted, or bonded to the plate.[1,2] Light in weight and comparatively much better strength[3] has made the Hat stiffened plates more popular among the structural engineers who preferably apply it in their designs. Using numerical analysis, it is proved that stiffeners with Hat section have reported several structural advantages over other types of open section[4] such as simple flat bar and 'L' and 'T' sections. Similar results are also obtained in the case of structures made of composite materials. As Hat stiffener integrated with a plate generates a closed section whereas 'L' and 'T' shape stiffeners form an open structure model. So better torsional rigidity characteristic of a closed section can be availed in the case of Hat stiffeners.[5] Additionally, the study has revealed that Hat stiffened panels succumb to only local buckling instead of global buckling.[6]

Vibration-based approaches are commonly used in practice for both diagnostic and prognostic studies of basic and indeed, complex structures. There are four major vibration-based damage detection or structural health monitoring technologies. These are named on the basis of vibration response parameters used, such as natural frequency, mode shape, curvature mode shape, and combined mode shapes and frequencies. The algorithms of these individual methods need to be identified at the beginning of the vibration-based damage detection work.[7-10]

Experimental modal analysis (EMA), one of the vibration-based nondestructive techniques, which is used for structural damage detections, provides flexibility and feasibility of real-time monitoring. Here atleast 5% change in the modal frequencies[11] is much sufficient to identify the existence of damage in the structure. To enhance the quality of the EMA of the Hat stiffened plate, need to fix five variables[12-14]

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How to cite this article: Karanjkar VA, Banerjee N. (2022). Modal Analysis of Diagonally Hat Stiffened Square Plate to Distinguish Spot Weld Rupture.

SAMRIDDHI : A Journal of Physical Sciences, Engineering and Technology, 14(3), 280-284.

Source of support: Nil

Conflict of interest: None

such as measurement locations, type of suspension for the structure, excitation technique, selection of accelerometer, and frequency response function analysis. It's essential to investigate the modal frequencies carefully as they may be observed higher for the damaged structure than an intact one. This can be seen in the case of composite laminated structures where local thickening in the delaminated region resulting from the matrix cracking increases the modal frequencies[15] even more than the original intact condition. If many spot welds are there, the degree of freedom of the Hat-plate model under analysis also increases. Therefore use of finite element analysis (FEA), which is the best technique available today[16-18], proved essential. Further, it can also be used to study Hat- Plate structures with dissimilar metals as well as composite materials.[19]

It seems that there is a scope for the study of a Hat stiffened square plate which can be investigated for weld rupture using experimental modal analysis because the literature also hardly finds such kind of work. In this paper, diagonally hat channel stiffened square plate assembly is tested using the experimental modal analysis technique. The plate and stiffener with same thickness and material are joined by a spot welding process. To assess the effect of weld rupture on the characteristics of the plate, it is tested for natural frequencies and mode shapes. These modal parameters are determined using the EMA technique before and after spot weld rupture. ANSYS version 15, an FEA software, is used to validate the results. In conclusion, a focus has been drawn on the relation of modal parameters with structural damages.

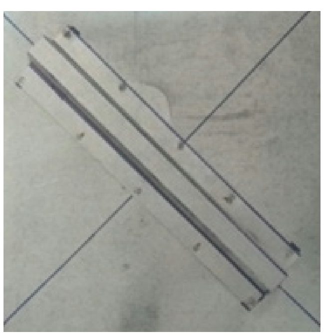

Figure 1. Hat stiffened plate

Modal Analysis

Theory

According to linear vibration analysis of the structure, the matrix equation for the Hat stiffened plate is represented as in Equation (1)

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \qquad (1)$$

Where, {x} = actual displacement coordinates at local level,
{p}= corresponding external forces,
{M}= corresponding inertia matrix,
{K}= corresponding stiffness matrix and
{C}= corresponding damping matrix.
Considering simple harmonic excitation, let:

$$\{p\} = \{P\}e^{i\omega t}, \{x\} = \{X\}e^{i\omega t}, \{\dot{x}\} = i\omega\{X\}e^{i\omega t}, \{\ddot{x}\} = -\omega^2\{X\}\epsilon \qquad (2)$$

Substituting Equation (2) into Equation (1), where {X} and {P} represent the displacements and applied forces, respectively gives,

$$-\omega^2[M]\{X\} + i\omega[C]\{X\} + [K]\{X\} = \qquad (3)$$

Now suppose,

$$\{P\} = i\omega[C] \qquad (4)$$

Then,

$$([K] - \omega^2[M])\{X\} : \qquad (5)$$

Thus when the applied forces exactly balance the damping forces, the structural modes excited are the normal modes of the un-damped system. In practice, it works well with relatively small applied forces.

Experimentation

A diagonally Hat stiffened square plate was considered for the investigation. A detailed geometry and dimensions of

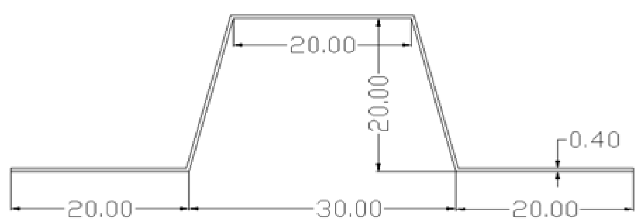

Figure 2. Dimensions (mm) of hat channel section (0.4mm thin)

Figure 3. Modal test using FFT Analyzer

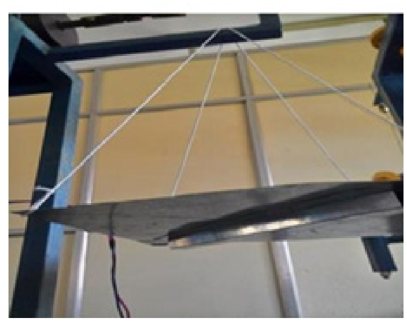

Figure 4. Modal test using FFT Analyzer [B.V.]

the Hat stiffened plate are shown in Figures 1 and 2. Here a stiffener is symmetrically placed on one of the diagonals of the plate. The rectangular plate dimensions are 300mm x 300mm, and the length of the stiffener is 300mm such that its ends do not merge with the plate edges. As the stiffener do not merge into the plate edges, the stiffness of the plate has been reduced. Five equally spaced (approx. 75mm apart) spot welds are applied on either side (i.e., on each flange) of the hat channel. The diameter of the spot weld is approx.7mm. Thus total of 10 spot welds have been used to assure a notable increment in the strength of the plate. Two assemblies of plate and stiffener made with steel sheets of thickness 0.4mm and 0.5mm separately are tested. The mechanical properties of the Hat-plate are testified as Poisson's ratio of the material is 0.3, the modulus of elasticity is 200 GPa, and the density is 7850 kg/m^3. A plate is held at its every diagonal end by a separate elastic and lightweight cord such that when suspended, both the cords cross over each other at pivot, as shown in Figures 3 and 4.

Theoretically, the said work is considered a free vibration analysis with free boundary conditions. In effect, this leads the actual structureto float in the space without any ground support but exhibiting rigid body behavior at zero frequency. Therefore to develop an experimental model, the square plate is suspended by very soft elastic chords. This way, the structure is constrained to a certain degree, and the rigid body modes would be exhibited at nonzero frequencies. If the support is more elastic, then the rigid body frequency levels come down much lower than the structural modal frequencies and become ineffective. Thus while selecting the elastic chords for test work, care is taken such that the rigid body modes have a negligible effect on the flexible modes.

An OROS 3-Series/ NV Gate. FFT analyzer set up is used to measure and analyze the plate vibrations. A piezoelectric accelerometer is placed at the center on flat side of the plate. For an excitation, method used here is SISO which involves an excitation at a single point. A broadband input is imparted through an impact hammer. An excitation has been given near an accelerometer. For the given input force and displacement /velocity/ acceleration response signals have been measured and fed to real time analyzer which processed the time domain data to produce FRFs. From the FRFs plots the frequencies corresponding to the first six consecutive picks were obtained as modal frequencies for further assessment. Both the spot welds at one of the ends of the stiffeners were sheared off. And the above modal test procedure was repeated for the ruptured spot weld condition of the stiffened plate.

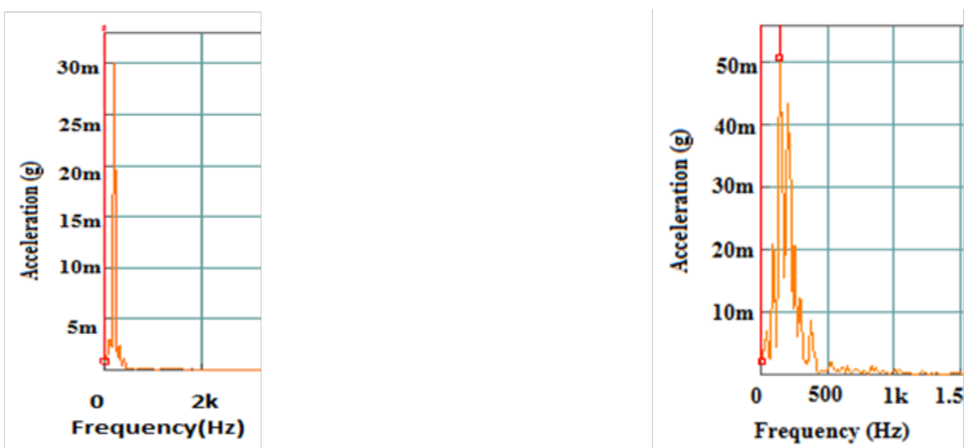

Figure 5. FRC of stiffened plate, 0.4mm thin, with (a) no spot weld ruptured and (b) spot welds ruptured

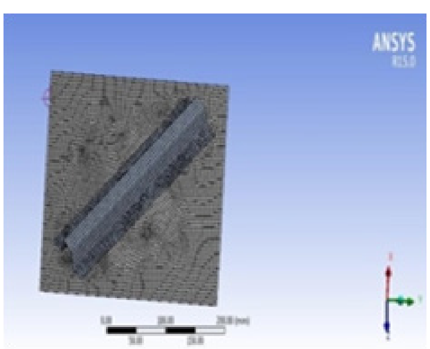

Figure 6. Meshed FE model

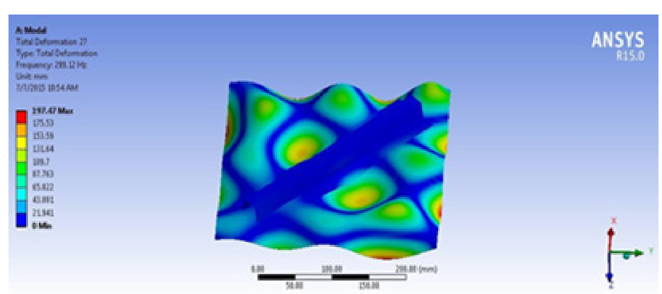

Figure 7. 6th mode shape with spot welds ruptured

Table 1: Modal frequencies of 0.4mm and 0.5 Mm thin stiffened plate with and without spot welds rupture using ema and fea techniques.

Mode nos.	*Modal frequency (hzs.) When no spot weld ruptured for 0.4mm thin plate*		*Modal frequency (hzs.) When 2 spot welds ruptured for 0.4mm thin plate*		*Modal frequency (hzs.) When no spot weld ruptured for 0.5 Mm thin plate*		*Modal frequency (hzs.) When 2 spot welds ruptured for 0.5 Mm thin plate*	
	Ema	Fea	Ema	Fea	Ema	Fea	Ema	Fea
1	100	97.74	37.5	41.97	50	31.6	12.5	19.1
2	200	191.72	87.5	83.97	112.5	112.6	100	112.1
3	300	301.80	137.5	135.99	200	168.1	175	168.1
4	400	399.47	200	196.51	237.5	233	225	233
5	525	512.04	250	246.17	287.5	253.1	287.5	253.1
6	575	569.19	300	299.12	325	301.2	312.5	301.2

Finite Element Analysis

The geometric model of the hat channel stiffened rectangular plate has been created in Pro/ENGINEER and saved in IGES format. The simulation of the plate assembly, intact and ruptured spot welds have been run with finite element analysis package ANSYS 15. Initially, the model of a hat channel stiffened plate assembly was imported through IGES format. A spot weld connections have been applied at the specified locations to complete the model. The constrained degrees of freedom are applied at the corners of the plate. The model is solved for modal analysis of intact and ruptured stiffened plate assembly to obtain the first six modal frequencies and mode shapes of the respective case. These modal frequencies have been compared with experimental modal frequencies for validation purposes (Figure 5).

Results And Discussion

Frequency response plots obtained by an EMA are as shown in Fig.5a and 5b for stiffened plate (0.4 mm thin) without spot weld ruptured as well as with both spot welds at one of the ends ruptured conditions. The first six consecutive modal frequencies and mode shapes obtained for all the tests are mentioned in Table 1. The initial larger decrement in the modal frequencies with spot weld ruptures is caused due to the generation of transverse cracks along with early stage separation phenomenon of stiffener and the plate at weld joints. By using an ANSYS software package for finite element analysis of the intact and ruptured spot welds conditions of stiffened plates, the initial six mode shapes and corresponding frequencies are obtained. The meshed model and sixth mode shape for 0.4 mm stiffened plate are shown in Figure 6 and 7, respectively. Similarly, results for the 0.5 mm stiffened plate are shown in Table 1.

Conclusion

The results from an experimental modal analysis and finite element analysis showed that the modal frequencies of hat channel stiffened plates with intact and ruptured spot weld conditions are a function of spot weld cracking. This causes the degradation of the material properties, and hence the global stiffness of the Hat stiffened plate decreases, consequently the modal frequency also. A careful interpretation of the obtained results is essential while using the vibration-based damage detection method, one of the NDT methods, to investigate diagonally Hat stiffened square plate. From the frequency response plot, it may be possible to measure the same modal frequencies for stiffened plates with ruptured welds and intact ones. This leads to deciding the number of modes to be considered. It can be concluded that initial modes are sufficiently extensive to detect the degradation of the material stiffness. Similarly, for a structure stiffened by adhesive bonds, EMA can be used to identify the dis-bond taken place. This leads to prove the applicability of EMA for the characterization and evaluation of the structural integrity of the stiffened plates.

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