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A model updating method for hybrid composite/aluminum bolted joints using modal test data

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ABSTRACT

The aim of this paper is to present a simple and applicable model for predicting the dynamic behavior of bolted joints in hybrid aluminum/composite structures and its model updating using modal test data. In this regards, after investigations on bolted joints in metallic structures which led to a new concept called joint affected region (JAR) published in Shokrollahi and Adel (2016), now, a doubly connective layer is established in order to simulate the bolted joint interfaces in hybrid structures. Using the proposed model, the natural frequencies of the hybrid bolted joint structure are computed and compared to the modal test results in order to evaluate and verify the new model predictions. Because of differences in the results of two approaches, the finite element (FE) model is updated based on the genetic algorithm (GA) by minimizing the differences between analytical model and test results. This is done by identifying the parameters at the JAR including isotropic Young's modulus in metallic substructure and that of anisotropic composite substructure. The updated model compared to the initial model simulates experimental results more properly. Therefore, the proposed model can be used for modal analysis of the hybrid joint interfaces in complex and large structures.

1. Introduction

The accurate prediction of structural dynamic characteristics such as the natural frequencies and damping ratios in order to vibration control and evaluating their performance in a dynamic situation is a significant aspect in the design of aerospace structures. Prediction and determination of the dynamic characteristics of the aerospace structures which are often composed of several parts or substructures depends on capability and ability of proper modeling of the joints interfaces. The joints usually cause a local increase in damping and decrease in stiffness of the structure and thus change its dynamic characteristics [1]. Therefore, accurate modeling of the joint regions is a necessary process to determine the dynamic behavior of large structures (composing of thousands of parts).

Nowadays, the increasing use of composite materials in combination with metallic parts in modern engineering structures has led to a new structural concept called hybrid structures [2]. In general, the hybrid metal-composite structures are divided into three main groups including steel/composite, titanium/composite and aluminum/composite. The first group are used mainly in navy structures [3–6], military vehicles [7], and also heavy transport vehicles [8]. The second group is usually

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used in aeronautical structures [9,10]. The third group sometime is used in electrical isolators [11], and electronic devices [12] but their major applications are in aircraft structures [13]. An important necessity in designing of these kinds of structures is the joining of two different materials with distinguishable properties which needs special considerations. The joining of metal-composite substructures may be executed by adhesive materials or mechanical fasteners or even a combination of two approaches. The bolted joint of metal parts with polymer matrix composites is a most common joining process in hybrid constructions for aeronautics and space applications [14].

A proper understanding of complex physics of the bolted joints interface region in composite structures and modeling of their performance and investigating their response in different loading conditions have been a concern for researchers for decades. In this area, numerous studies on the mechanically fastened joints of composite materials and structures can be found in review papers [15,16].

Investigating the parameters such as the joint geometrical dimensions [17–19], the effects of stacking sequences on joint strength [20–23], bolt preload [17,23], bolt diameter [18,24], the number of bolts [25,26], the bolt head type [27], the clearance between the bolt and hole [28–30], the geometrically nonlinear effect [31] and material nonlinearity [32], the effects of high temperatures [33], hysteresis effects [34] and the combined effect of bolted and bonded joints [35] under different loading conditions are attractive topics for researchers in this area. However, few studies have been done regarding the dynamic behavior and dynamic characteristics of the joints in composite structures [36,37]. Moreover, few studies have been focused on the design and analysis of joints in hybrid aluminum/composite structures. In these researches, topics such as the secondary bending effect [38], load transmission capacity [39], and failure mechanism [40,41] have been investigated.

Due to increasing utilization of the hybrid structures in aircraft industries, accurate modeling of hybrid joint interfaces in order to investigate their effects on structural dynamics characteristics is going to be more important than ever. But modeling of joints in hybrid structures is a difficult process, because, in addition to intrinsic complexity of joint interfaces [42], there exist many uncertainties in modeling of behavior and properties of composite materials and complexities of failure mechanisms in them [43]. Moreover, a detailed 3-D modeling of joints may lead to a considerable computational runtime and cost; for this reason, evaluation of the failure mechanisms in bolted composite structural joints have been based on experiments at past decades [44].

On the other hand, analytical methods in dynamic modeling of joints in addition to complexity usually do not yield accurate results [45]. The difficulty is not here, how to model but the question is what should be modeled [46]. Considering the joint mechanics and parts interfaces accurately, including nonlinear effects, slipping, energy lost and probably non-continuous behavior effects requires overcoming some current limitations and better understanding of joint physics and parts interfaces [42]. Therefore, developing the parametric models for the uncertain structural parts including supports and joints have been an interesting subject for the researchers for a long time. In this regards, a simple and accurate parametric model is necessary to simulate dynamic behavior and especially, modal analysis to determine dynamic characteristics such as the natural frequencies and damping ratios.

In general, two approaches are used for extracting dynamic characteristics of complex structures which are experimental (modal testing) and numerical (finite element analysis) methods. Today, structural dynamics analysis is mostly carried out by using commercial FE analysis software. These software can yield only an estimation of eigenvalues of the system due to simplifying procedures in simulation process and also due to lack of proper elements in order to precise modeling of some critical regions such as the bolted joints. Therefore, the predicted structural dynamics behavior using FE models are different from their observed behavior in practice [47].

Parameterization of some critical structural parts such as supports and joints and assign some proper values to these parameters is an effective solution in modeling process, although, parameterization of joints is a difficult procedure [47]. Output data of the analytical model such as the natural frequencies and mode shapes are often sensitive to little variation of these parameters and incorrect values of the parameters may lead to the mistake results. Using the experimental results associated with a model updating technique is considered as a well-known method for modifying these parameters. the parameters can be longitudinal stiffness (EA), bending stiffness (EI) or they can be geometrical dimensions or elastic properties like young modulus and poison ratio of a specified region of structure such as joints.

FE model updating is, in fact, a method to refine and correct the incorrect assumptions in modeling process via adjusting the model parameters based on the experimental results [47]. Model updating methods are divided generally into two main groups including direct and indirect [48,49]. Nowadays, the indirect or iterative methods are used largely based on a sensitivity analysis [50]. In this approach, some special parameters of the model can be modified such that an objective function containing a difference between the predicted values by finite element method and measured data are minimized. Therefore, the experimental methods are introduced as an alternative approach to the development of mathematical models of the structural joints, i.e., by creating an initial theoretical model and using experimental data it is possible to improve the model behavior [1]. The modal testing results are used in order to correcting the model parameters or model updating. The updated model can provide a more accurate simulation of the joints [51].

According to a literature review, the lack of adequate researches in the area of hybrid structure vibrations can be observed. The aim of this paper is to propose a simple, accurate and proper model for simulation of dynamic behavior of bolted joints in hybrid aluminum/composite structures, such that, the errors due to incorrect modeling of joints in predicting natural frequencies can be minimized. Therefore, “doubly connective layer” model is proposed in this paper for finite element modeling of joint interfaces in hybrid structures and then the model is updated using genetic algorithm.

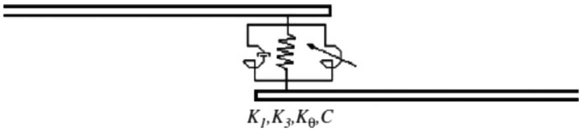

Fig. 1. Spring-damper model of the bolted joint [53].

The reliable models are usually obtained using experimental measurements. Therefore, the results of modal testing are used to correct or update the model parameters. Due to discrepancies between experimental results and theoretical model prediction, a model updating procedure according to a genetic algorithm optimization process is performed in ANSYS software, where the differences between numerical and experimental natural frequencies as the objective function are minimized and the model parameters are identified.

2. Background of bolted joints modeling methods

In this section, the conventional methods for joints modeling in metallic structures are firstly studied in order to evaluate the position and potential of each one compared to hybrid structures.

The simplest method for modeling the joint interfaces of a structural system is merging the collocating nodes of the mating substructures at the joint region. The results of this method are not rather valid because of not taking the flexibility of the joint region into account [52]. Applying this method to the model is easy and in fact (actually) structural discontinuity is eliminated. This method is appropriate for estimating the structural behavior in early design stages. Since there is no parameter in this model, it is not a proper approach for using in model updating.

The second method is the use of the lumped mass-spring system for joint interface area [53,54]. In this method which is applicable for simple systems, the translational and torsional springs with viscous dampers are used for stiffness and damping properties of the joint region (Fig. 1). The joint effect in this model is concentrated at local points which is not a real assumption, whereas, the real joint region consists of length and area such that its effects develops to a distributed region. This method is probably the oldest one which has been used for bolted joint modeling so far and is appropriate for simple models. However, it is not suitable for large structures due to high degrees of freedom. The concentration of the distribution effect at some specified points of structure- sometimes at one point only- and increase of stiffness in some specified directions at joint region in comparison with stiffness of neighbouring elements is one of the disadvantages of this method.

In the third method, the so-called generic elements are used for joint modeling, Fig. 2. In generic model, the interactions between all joint degrees of freedom are considered and the distributing effects of the joint are taken into account [55]. Therefore, the generic model is a more realistic model for the joint region. The success of this method is dependent upon the understanding of joint nature and skillful decrease of the number of independent parameters in generic elements. However, using this method in FE software is not accomplishable easily.

The forth method of joint modeling is a nonlinear model known as Iwan's model [56]. This model is composed of a parallel system of spring-slider elements known as Jenkins elements. The Iwan's model is shown in Fig. 3. This method which is essentially a nonlinear model has been proposed for simulating elasto-plastic behavior of metals. In this model a distributed system of Jenkins elements are used which is appropriate for micro- slip modeling.

All above mentioned methods can be employed properly for modeling of simple structural systems; however, they are usually restricted for using in complex structural systems which contain thousands of joints and high degrees of freedom.

In the fifth method, an interface layer is used between two mating substructures. This method is divided into two groups of elements. The first group contains zero thickness interface elements in which a constitutive equation is attributed between normal and shear stress components [57]. In the second group, the interface elements have a small thickness such that their behavior is similar to the other elements of the FE model. In Fig. 4a schematic picture of the interface element model with a small thickness is shown. In this model, it is assumed that the behavior of the 3-dimensional interface elements is controlled by different properties of the surrounding elements [58]. This method has the capability of using in large structures, but it produces a separate layer from substructures in the interface region, so increases the mass and also change the structure dimension.

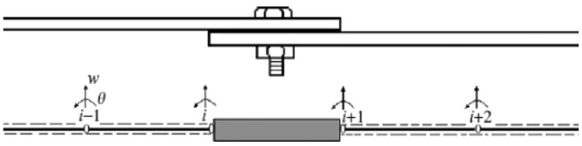

Fig. 2. Bolted joint modeling by generic element [55].

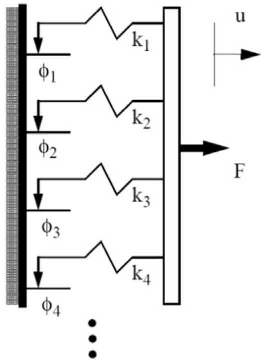

Fig. 3. Modeling of bolted joint by Jenkins elements [56].

Fig. 4. Modeling of bolted joint by interface element [58].

3. JAR methodology

The new approach proposed recently for simulating the dynamic behavior of the joint interfaces is the connective layer model [59]. This model is based on the concept of joint affected region (JAR) where a schematic of the model is shown in Fig. 5. In this method, it is assumed that the decreasing stiffness effect of the bolted joint is extended to a specified region of the substructures. Therefore, an equivalent zone in the neighborhood of the interface region is considered as JAR. The thickness of JAR depends on various parameters such as the joint pre load, surface roughness, the substructures materials and etc.

The JAR has been modeled by 3D connective elements with unknown properties, Fig. 6. The parameters of this model are the elastic properties of connective layer which are identified and adjusted by comparing to experimental results. Since, there is not any layer between the substructures; the structural dimensions are not changed. Moreover, since the element densities are assumed to be equal to that of substructures elements in the joint affected region, the total mass of the structure remains unchanged. This model is applied successfully by Shokrollahi et al. [52] and Shokrollahi and Adel [60] for dynamic behavior modeling of bolted joints in aluminum/aluminum and steel/steel structures, respectively.

The main approach in present research is the investigation of elastic behavior of the hybrid bolted joints and its effect on the dynamic response of hybrid structures. Therefore, defining a region affected by elastic behavior at two sides of the joint interface is sufficient for this purpose. This region is composed of two distinct layers, one layer with isotropic properties in metallic substructure and the second layer with an orthotropic behavior in composite substructure. This model is an extension of connective layer model as mentioned before [52,60].

A schematic picture of this model is illustrated in Fig. 7. The presented model is based on a macro-scale approach and is useful for displacement computation and eigenvalue problems such as the modal or buckling analyses. This model has 4 parameters including elasticity module E in isotropic region and elasticity modules E_x, E_y, E_z in orthotropic region.

In developing process of “doubly connective layer” model for modeling of hybrid metal/composite bolted joint interfaces, the following assumptions and features are considered:

I- The structure mass does not change, II- The structure dimension does not change, III- Having the ability to simulate of dominant properties in joint vibrational behavior such as stiffness reduction in joint position, IV- The model parameters be identifiable according to a regulate method from experimental results, V- The number of model parameters to be as low as possible, such that one can identify them by experimental limited data, VI- The developed model to be applicable to large structures, and VII- The model to be attachable to the finite element commercial software.

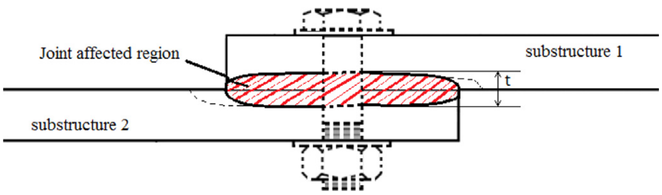

Fig. 5. Bolted joint affected region [59].

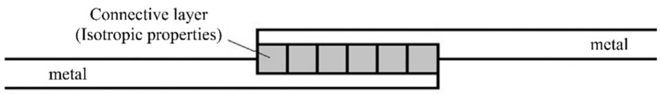

Fig. 6. Modeling of a bolted joint by connective element in a metal/metal joint [52,60].

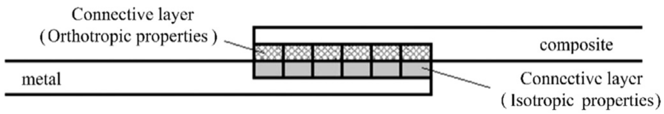

Fig. 7. Modeling of a hybrid bolted joint by doubly connective layer.

In the model presented in Fig. 7, there are all the features listed. Because, firstly, the density of the layers in the JAR is the same as neighboring elements of the substructures, so, the structure mass does not change. Secondly, since there is not any interface layer between the substructures, the structure dimensions do not change. Thirdly, by decreasing the elastic properties in JAR it is possible to decrease the local stiffness of the structure which is the most significant effect of the bolted joint in the linear behavior range.

Fourthly, the model parameters including elastic properties of connective layers have a significant effect on natural frequencies. By comparing the natural frequencies obtained from finite element and test results and then minimizing the differences between them, the parameter values can be identified by optimization process. Fifthly, only four parameters (one parameter for isotropic region and three parameters for orthotropic region) are necessary for the model to perform the required simulation. Sixthly and seventhly, the model can be used easily for simulation of joints interfaces at large structures, even using the finite element commercial software.

4. Case study

Geometrical dimensions of hybrid construction which is considered for investigation, and consisting of the 7075-T651 aluminum alloy and carbon/epoxy composite beams are shown in Fig. 8. The dimensions of two beams are the same and the length of the joint region is 60 mm. Fig. 9 shows the Aluminum substructure having dimension of $443 \times 42 \times 8.7$ mm^3. The elastic properties and density of the beam are given in Table 1.

The composite material used in this study is a T300 woven carbon fiber and LY5052 epoxy resin system. Thin laminates with a configuration of a quasi-isotropic layout $[[(0/90)_4/(\pm 45)_4]_2/(0/90)/(\pm 45)]_s$ are fabricated, giving the laminate an approximately 8.7 mm thickness. The composite laminates are manufactured by hand lay-up and cured under recommended process. Then, the beam with 443 mm length and 42 mm width are cut from the prepared panel using a low speed diamond saw and are polished using sanding rotor equipped with a fine sand paper (grit #800), Fig. 10. The fiber volume fraction of the composite layers is also 40.7%. The properties of the each lamina are given in Table 2.

Here, the composite beam properties using the data in Table 2 and the employing the following equations [61] are calculated and listed in Table 3.

$$E_x = E_y = \frac{2E_1\left[E_1+2(1+\nu_{12})G_{12}\right]}{(3+\nu_{12})E_1+2(1-\nu_{12}^2)G_{12}} \tag{1}$$

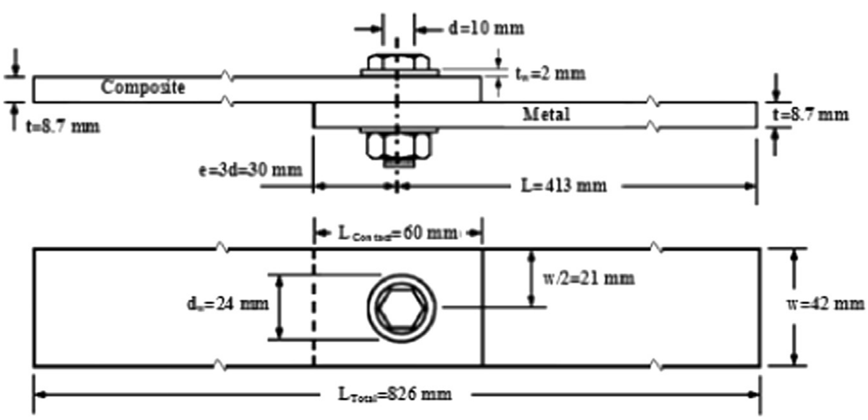

Fig. 8. Geometrical dimensions of hybrid structure.

Fig. 9. 7075-T651 Aluminum alloy beam.

Table 1
Physical and mechanical properties of 7075-T651 alloy.

E (GPa)	G (GPa)	ν	ρ (gr/cm^3)
71.7	26.9	0.33	2.81

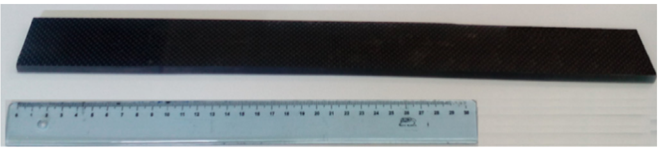

Fig. 10. Woven carbon/epoxy composite beam.

Table 2
Mechanical and strength properties of carbon/epoxy lamina.

$E_1 \approx E_2$ (GPa)	E_3 (GPa)	G_{12} (GPa)	$G_{13} \approx G_{23}$ (GPa)	ν_{12}	$\nu_{13} \approx \nu_{23}$	$X_{T1} \approx X_{T2}$ (MPa)	S_{12} (MPa)
55.69	9.28	4.18	4.64	0.047	0.466	524.08	43.13

Table 3
Mechanical properties of the woven carbon/epoxy composite beam with a quasi-isotropic lay-up.

$E_x \approx E_y$ (GPa)	E_z (GPa)	G_{xy} (GPa)	$G_{xz} \approx G_{yz}$ (GPa)	ν_{xy}	$\nu_{xz} \approx \nu_{yz}$	V_f	ρ_c (gr/cm^3)
40.32	9.28	15.39	4.64	0.31	0.34	40.7%	1.365

$$\nu_{xy} = \frac{(1 + 3\nu_{12})E_1 - 2(1-\nu_{12}^2)G_{12}}{(3+\nu_{12})E_1 + 2(1-\nu_{12}^2)G_{12}} \tag{2}$$

$$G_{xy} = \frac{1}{2}\left(G_{12} + \frac{E_1}{2(1+\nu_{12})}\right) = \frac{E_x}{2(1+\nu_{xy})} \tag{3}$$

$$E_z = E_3 \tag{4}$$

$$G_{xz} = G_{yz} = G_{13} \tag{5}$$

$$\nu_{xz} = \nu_{yz} = (E_x/E_1)\nu_{13} \tag{6}$$

The use of quasi-isotropic laminates usually leads to reduce stress concentration in structural parts containing mechanical joints [14,62]. Also, this layout is optimized when the loading direction is not known or multi-direction on the structure [63]. It should be noted that there is possible to design lighter and more efficient structures with fiber orientation in the loading direction, but in many parts of aircraft due to lack of predictable stresses and their directions, the use of quasi-isotropic laminates is more common [64].

The hybrid structure after assembling the aluminum and composite substructures with a bolt and nut is shown in Fig. 11. The assembly process is conducted using a bolt and nut with a diameter 10 mm and two gaskets. Recommended torque

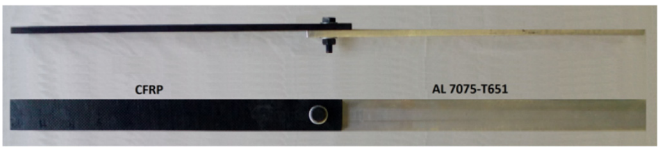

Fig. 11. The hybrid structure under consideration in present research.

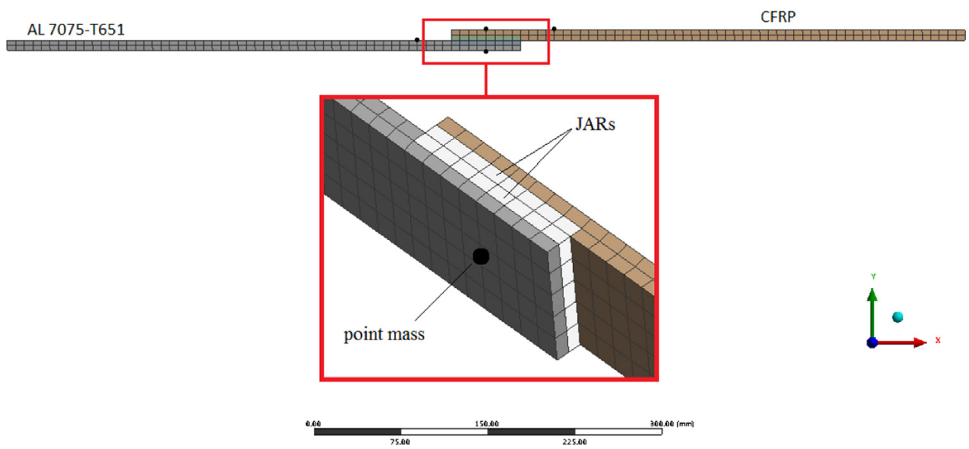

Fig. 12. FE model of the hybrid joint.

values to apply to fasteners vary from industrial specifications, fastener type, fastener material and strength or specific applications. Ref. [65] is the guideline used to specify torque values and ranges for mechanical fasteners in composites. According to this guideline, the applied pre-load torque is equal to 38 N m.

5. FE modeling

It is possible to develop accurate 3D models for hybrid joints using FEM, however, in practice, due to very high degrees of freedom, their application in complex structures are restricted. The alternative solution is employing a simple FE model for the joint region and modifying the behavior of the model using measured vibration data.

The FE model is created using the ANSYS software which is illustrated in Fig.12. In this model the sensors and bolt and nut are simulated by concentrated masses. Due to preference of higher order elements over the lower order elements, the elements used in metal, composite and the joint affected region are 3D elements with 20 nodes per element (solid186). The main difference is that in composite substructure the elements have orthotropic properties whereas in the metallic substructure the elements have isotropic properties. (Fig. 7). This model consists of 1200 elements and 7978 nodes. The mode shapes resulted from FEM eigen-solution is shown in Fig. 13.

In the initial FE model, the elastic properties of the JAR are the same as neighboring elements and corresponding nodes are merged to each other in joint interface. In the first case, the mass of the bolt, nut, and fasteners are neglected and in the second case the point masses are used instead. The results of the natural frequencies obtained from FE analysis are given in Table 4.

6. Modal test

In this section, the modal test is done to evaluate the structural vibration behavior, and the obtained results are used to identify the joint parameters. Fig. 14 shows the modal testing of the hybrid structure with free-free boundary condition. In order to determine the natural frequencies of the hybrid structure, an impact hammer is used for excitation and the structure frequency response functions are measured. Applied force is measured using the existing force sensor on the hammer head. It should be noted that to achieve higher accuracy, three impacts are applied in the excitation point.

Theoretically, the natural frequency can be measured only with an accelerometer, but given that the mass of sensors is small compared to the mass of the main structure, it is better to use two accelerometers symmetrically at two sides of the joint, at points A and B in Fig. 14, for obtaining more reliable recorded data. Each sensor with 10 gr mass is added to the FE model as a point mass. The mass ratio of the accelerometers to the main structure is approximately 3 % which is within the 10% allowable range [66]. The total mass of the main structure is 675 gram.

The time domain signals are recorded and conditioned by the software YE7600, and the signal post-processing is performed by N-modal 5.0. The frequency response of the hybrid structure at the frequency range of 0–1300 Hz is shown in Fig. 15, which corresponds to excitation and response at point A. The results of the natural frequencies obtained from Fig. 15 are given in Table 4.

The following points are derived by comparing the errors in Table 4;.

I. neglecting the mass of the sensors and bolts can affect the structural dynamics, especially in large structures with many joints. The mass of the bolt and nut in the structural assembly is nearly 58 gr such that the ratio of this mass to structure mass is %8.6. Moreover, the mass ratio of the sensors and bolt to structure is nearly %11.6. II. Frequency errors in even modes

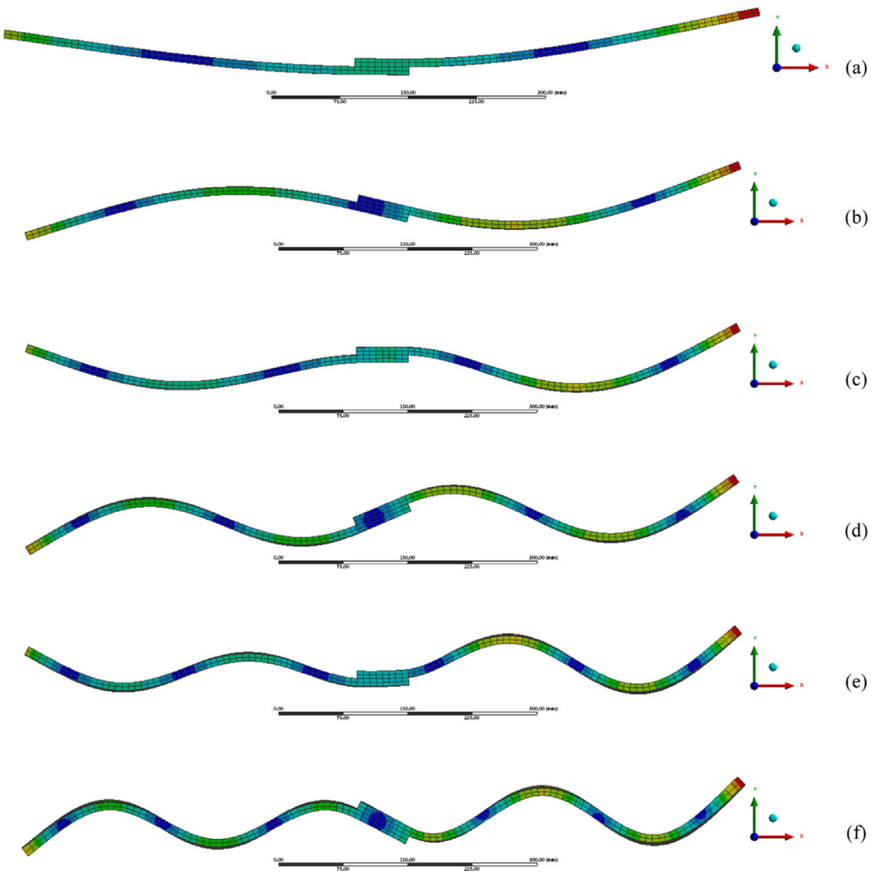

Fig. 13. The mode shapes from FEA. (a) the first mode shape (b) the second mode shape (c) the third mode shape (d) the forth mode shape (e) the fifth mode shape (f) the sixth mode shape.

Table 4
The natural frequencies of hybrid structure obtained from test and initial FE models.

Mode	Test frequency (Hz)	Initial FE model frequency (without considering bolt and sensors mass) (Hz)	Error (%)	Initial FE model frequency (with considering bolt and sensors mass) (Hz)	Error (%)
1	64.98	70.43	8.39	68.07	4.76
2	189.59	191.36	0.93	189.07	-0.27
3	346.15	377.28	8.99	366.06	5.75
4	590.57	612.72	3.75	598.80	1.39
5	870.30	948.98	9.04	931.37	7.02
6	1191.36	1267.50	6.39	1230.20	3.26

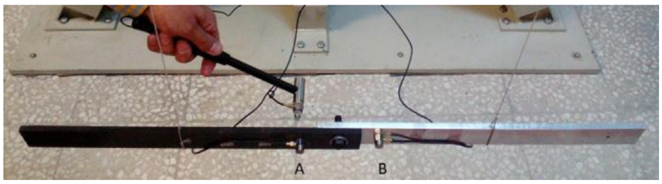

Fig. 14. Hybrid structure modal test set-up.

are smaller than odd ones, since joint position in even modes are placed in nodal position of that mode shape. Thus, it does not have any participation in structural dynamics. However, for the odd modes, the joint is located in peak amplitudes where it has the maximum displacement. If the excitation amplitude is large, it can be led to micro-slip in contact surface which in turn can cause nonlinear behavior in the joint region, III. It is seen that in general case, large errors do not exist, i.e. the errors of all modes are less than 8%. One reason may be that the mechanical properties of metallic and composite

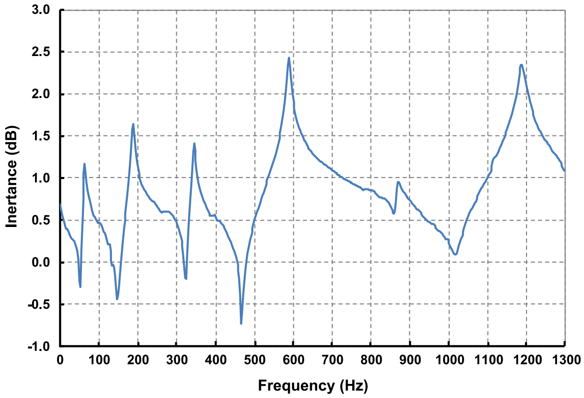

Fig. 15. Frequency response function.

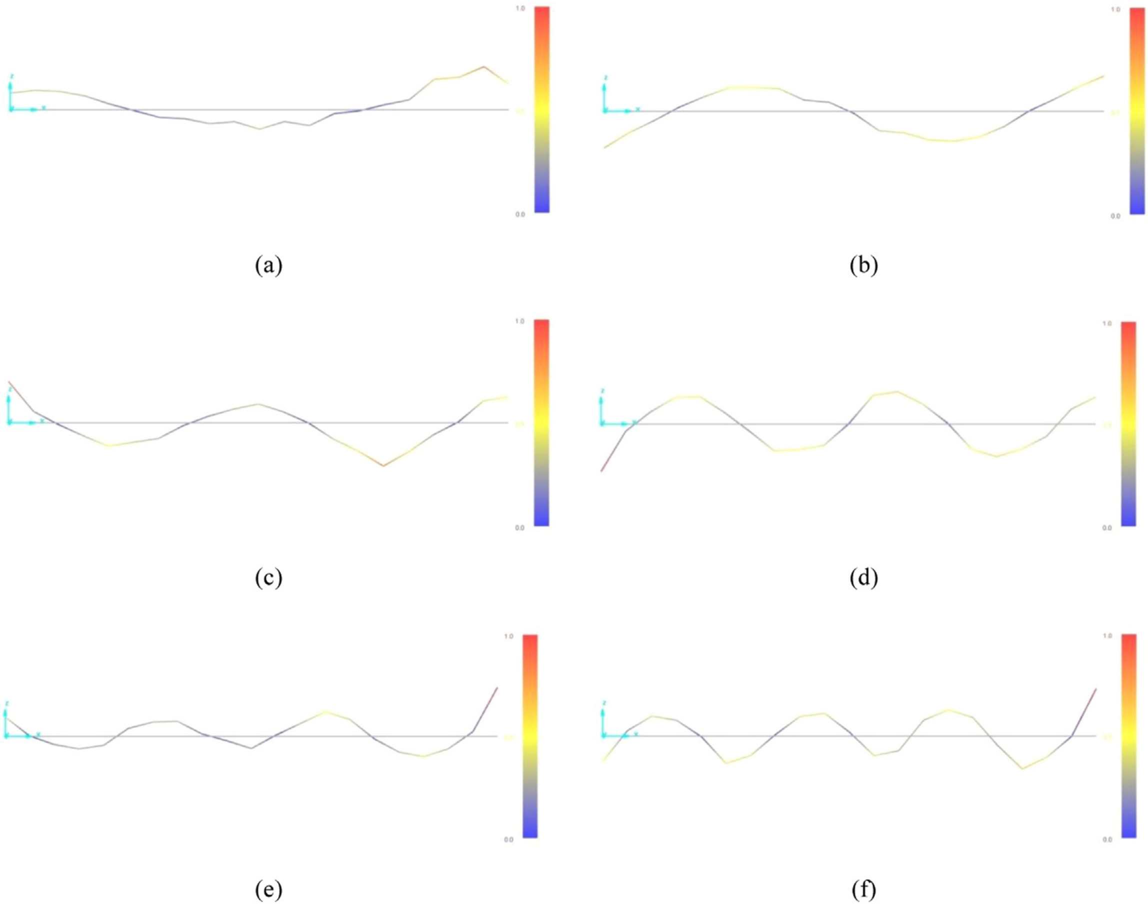

Fig. 16. The experimental mode shapes. (a) the first mode shape (b) the second mode shape (c) the third mode shape (d) the forth mode shape (e) the fifth mode shape (f) the sixth mode shape.

substructures are extracted by mechanical tests and are substituted in the model. Therefore, the modeling error due to uncertainty of mechanical properties of substructures is minimized. Considering the above mentioned point, it can be deduced that the main reason for differences in the test and FE model (Table 4) frequencies is due to inaccurate modeling of the joint region. IV. The errors of all modes except second and forth modes are out of acceptable range, Inasmuch as the error of natural frequencies in critical structures like launch vehicles and aircraft should be less than 2–3% [67]. Therefore, it is necessary that the numerical model be updated by using modal test data as given in next section. The experimental mode shapes of the hybrid structure are shown in Fig. 16.

Table 5
Composite beam natural frequencies obtained from test and FE model.

Mode	Test frequency (Hz)	Initial FE model frequency (Hz)	Error (%)	Updated FE model frequency (Hz)	Error (%)
1	259.37	265	2.17	256.4	-1.14
2	695.41	710	1.80	685.8	-1.38
3	1298.24	1350	3.97	1301.8	0.27
4	2121.53	2245	5.82	2121.12	-0.02

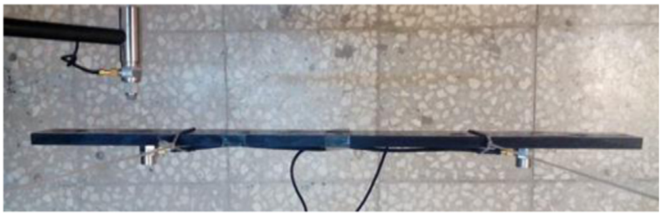

Fig. 17. Composite beam test setup.

Table 6
Comparison of the natural frequencies of hybrid structure obtained from test and updated FE model.

Mode	Test frequency (Hz)	Updated model frequency (with doubly connective layer) (Hz)	Error (%)
1	64.98	63.96	-1.57
2	189.59	188.38	-0.64
3	346.15	347.40	0.36
4	590.57	590.27	-0.05
5	870.30	888.46	2.09
6	1191.36	1195.90	0.38

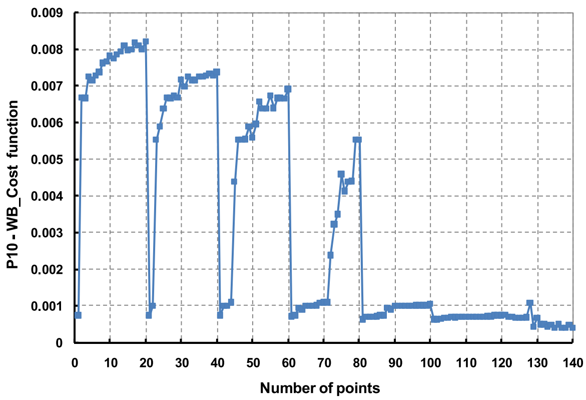

Fig. 18. Minimization of the objective function along the model updating process.

7. Model updating

The model parameters are identified by minimization of the differences between the measured natural frequencies and corresponding predicted values from FE model. The objective function is defined in Eq. (7). This function is the summation of square of errors between four first experimental and analytical frequencies.

$$\text{Min} \sum_{j=1}^{4} w_j \left[\frac{f_j^{(a)}}{f_j^{(e)}} - 1 \right]^2 \text{with } w_j \geq 0 \text{ and } \sum_{j=1}^{4} w_j = 1 \tag{7}$$

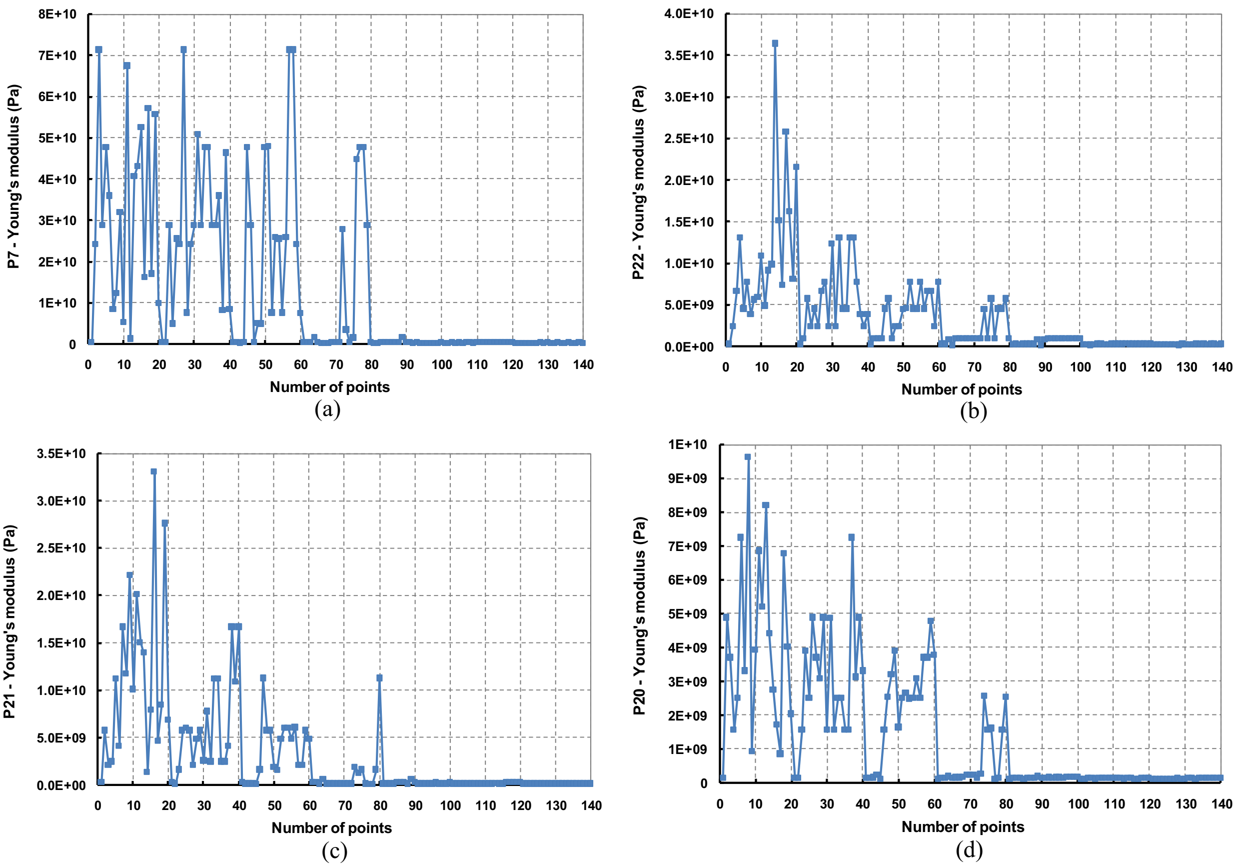

Fig. 19. Convergence of model parameters along the updating process for aluminum and composite parts; (a) Parameter E, (b) Parameter E_x, (c) Parameter E_y, (d) Parameter E_z.

where $f_j^{(a)}$ and $f_j^{(e)}$ are analytical (from FE model) and experimental (from modal test) natural frequencies and w_j is the weighted coefficients corresponding to each mode. Since in this research, no mode is preferred with respect to other ones, and it is assumed that all modes are measured with the same accuracy, so, all weighting coefficients are taken to be unity. The objective function is defined in Excel program as a calculator and by defining proper parameters; its link to ANSYS is performed [52].

In this section, the model updating of only composite beam has been performed. The beam has a free- free end condition as illustrated in Fig. 17. Two accelerometers are used at a distance of 78 mm from the ends of the beam. The excitation is by the impulse hammer where the impacts are entered to the back of each sensor. The natural frequencies of composite beam obtained from test and initial and updated FE model are listed in Table 5.

The application of GAs for FE model updating has recently attracted more interest [68]. Because of the existed problem with multiple objective functions for model updating; in this research, an optimization process using genetic adaptive multi-objective optimization algorithm is performed. According to Eq. (7) it can be seen that the fifth and sixth frequencies have not been used in optimization process, which is due to the fact that one be able to find an assessment to evaluate the updated FE model prediction for higher natural modes.

The natural frequencies obtained from updated FE model of hybrid structure are listed in Table 6. As can be seen, the first four modes which are participated in updating process are in a good agreement with test results. Moreover, the updated model predicts the fifth and sixth natural modes properly.

Figs. 18–20 illustrate the convergence of objective function, model parameters and natural frequencies along the updating process. Fig. 18 shows the objective function minimization in optimization process using genetic algorithm. As it can be seen from this figure, the optimization process is converged after seven iterations where 20 design points have been assessed in each iteration.

The convergence process of the updating parameters to their final values along the updating process is shown in Fig. 19. Also, the convergence process of the first four natural frequencies of model to their experimental counterparts during the updating process is presented in Fig. 20.

Initial and final values of the FE model parameters are listed in Table 7. It is observed that the Young's modulus for isotropic elastic region has been reduced about 379 times lower than the values in initial value. Also, the values of modulus

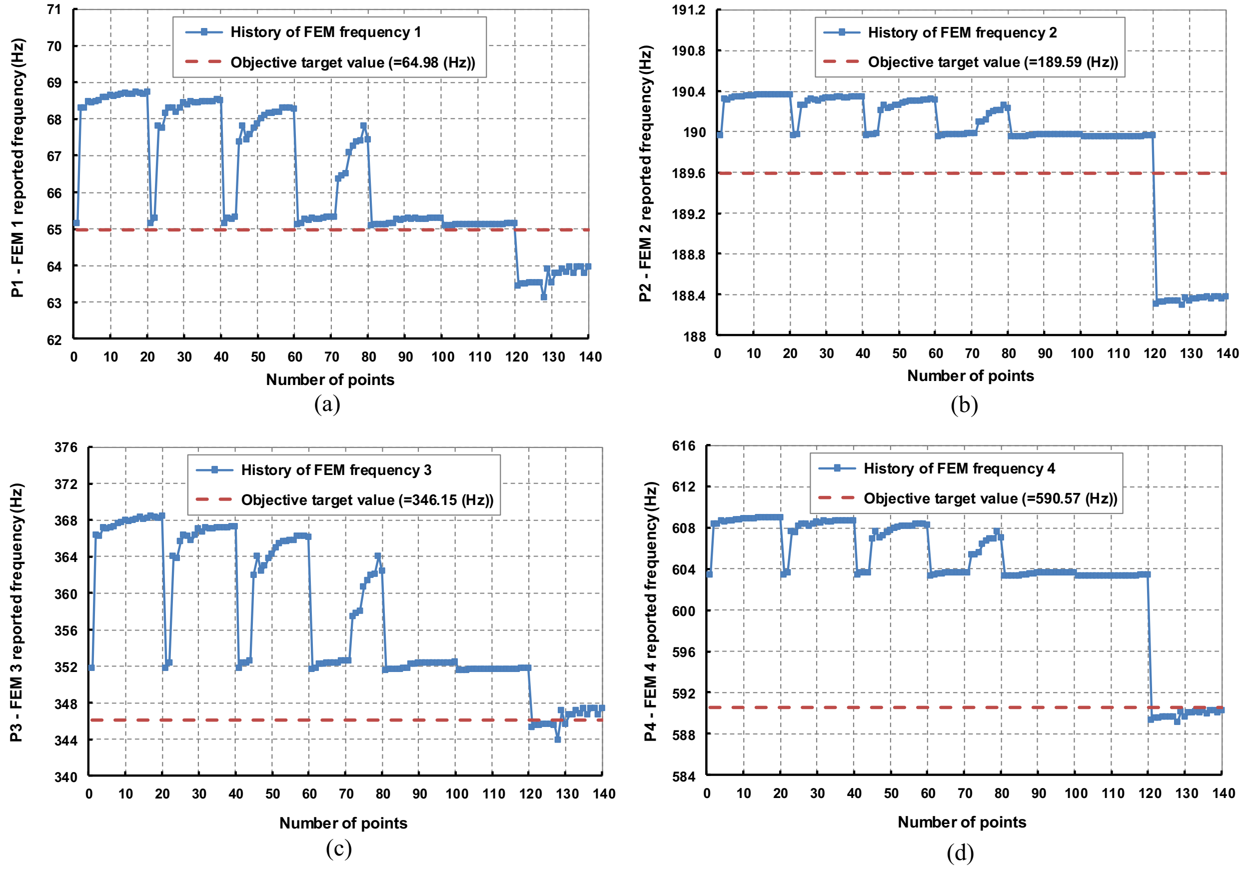

Fig. 20. Convergence of natural frequencies along the updating process; (a) first natural frequency, (b) second natural frequency, (c) third natural frequency, (d) forth natural frequency.

Table 7
The final values of the model parameters at the end of updating process.

Parameter	Isotropic layer	Orthotropic layer		
	E	E_x	E_y	E_z
Initial value (Gpa)	71.7	40.32	40.32	9.28
Final value (Gpa)	0.189	0.263	0.129	0.142
Reduction order	379	153	312	65

in the x, y and z-directions in the orthotropic elastic region have been reduced about 153, 312 and 65 times, respectively. These results indicate that the modulus has the maximum effect on flexural behavior of the composite beam in x and y-directions.

8. Conclusion

The main focus of this research is to study the elastic behavior of bolted joints and its effect on the dynamic characteristics (especially natural frequencies) of hybrid structures. Because of the complex nature of the joint interfaces, description of joint dynamics by analytical models is very difficult. In this regards, this paper presents a simple, accurate and reliable model in order to determine vibration characteristics in hybrid aluminum/composite structures.

For this purpose, using the concept called "joint affected region" a new approach called "doubly connective layer" which is in fact an equivalent 3D model for bolted joints interfaces in hybrid aluminum/composite structures is presented. The "doubly connective layer" model comprises one layer with isotropic elastic behavior in metallic substructure and another layer with an orthotropic elastic behavior in composite substructure. This model has 4 parameters including Young's modulus in metallic substructure and modulus in three directions in composite substructure which are identified by experimental measurements and model updating process. The results of the updated model have been shown a good agreement with experimental results and the experimentally measured data has been predicted properly. In addition, the model can predict well the higher modes of the structure that are not involved in the process of updating and optimization. The initial stiffness of the joint affected regions in metallic substructure is reduced about 379 times and that of composite substructure is reduced 153, 312 and 65 in x, y and z-directions, respectively. The results indicate the reduction in structural stiffness occurs in joint position which is the most significant effect of the bolted joints in their linear behavior range.

The proposed model can be easily attached to commercial finite element software in order to accomplish modal analysis of the joint interfaces of the large and complex hybrid structures. The most important feature of the proposed model is simple in framework and efficiency in computing, so that it can be used easily in dynamic analysis of large and complex structures such as wings and fuselage of aircrafts, ships and missiles that included a lot of hybrid joints.

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