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Finite Element Modelling for the Dynamic Behaviour Analysis of a Structure with Hi-Lok Fasteners

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ABSTRACT

The number of Hi-Lok fasteners used in the assembly of aircraft structures is very high. For this reason, an efficient modelling technique is required to accurately analyse the dynamic behaviour of the structures. In this study, a modelling technique with special emphasis on Hi-Lok modelling is proposed to analyse the dynamic behaviour of a test structure with Hi-Lok fasteners. Four different finite element (FE) models to represent the test structure with the Hi-Lok fasteners were developed using MSC Software packages. The natural frequencies and mode shapes obtained from the FE models are compared with those of the Experimental Modal Analysis (EMA) in terms of total error, computational time and memory disk usage. It was found that the model D with the simplified beams representing Hi-Lok predicts the dynamic behaviour of the test structure with an accuracy of 96.6% and with comparatively low computational time and memory disk usage. This proposed modelling scheme may provide useful approaches to aircraft researchers and engineers for the dynamic analysis of the structures.

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Introduction

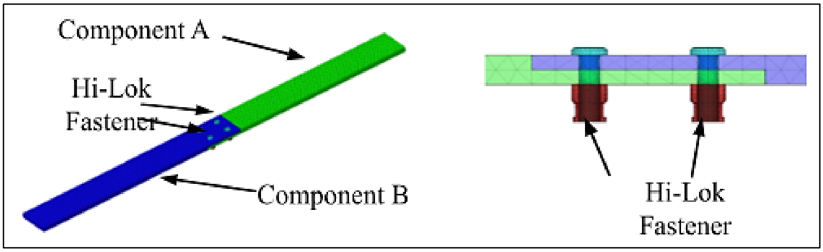
Hi-Lok fasteners are the most commonly used fasteners in the assembly of aircraft components and substructures due to their advantages such as higher strength, lightweight, easy and fast assembly, good stress concentration factor, cost efficiency and correct torque application [1]-[8]. However, the presence of Hi-Lok fasteners in assembled aircraft structures has a significant impact on the dynamic behaviour of the aircraft structure due to the numerous physical mechanisms associated with the fasteners. Due to the complicated physical relationships, these fasteners lead to large uncertainties in modelling. Therefore, accurately and economically modelling the dynamic behaviour of a structure with Hi-Lok fasteners is a very challenging process that needs to be investigated further.

Appropriate analytical models help researchers and engineers to better understand the dynamic behaviour of fastened structures. Over the past decades, many researchers have studied the behaviour of bolted joints and fasteners and their effects on the response of structures. Various modelling techniques have been proposed [9]-[14]. Among the widely used techniques are the solid bolt model, coupled bolt model, spider bolt model, RBE bolt model, hybrid bolt model and no-bolt model [15]-[17]. Most researchers used CBAR or CBEAM elements to represent the bolt shanks and RBE elements to connect bolt heads and nuts to components. Recently, several researchers [18]-[21] have shown the representation of bolted joints using CBEAM and RBE elements for the dynamic behaviour analysis of assembled structures. However, they mainly focus only on the simplified and accurate modelling of bolted joints for dynamic behaviour analysis, and not on how to incorporate different types of 1D elements for modelling Hi-Lok fasteners. Very little work has been carried out to propose modelling scheme for the dynamic behaviour analysis of structures with Hi-Lok fasteners, which is not entirely clear and needs clarification and further investigation.

This study proposes a modelling scheme with special emphasis on Hi-Lok modelling for the analysis of the dynamic behaviour of an assembled structure with Hi-Lok fasteners. The test structure with Hi-Lok fastener for this study consists of two substructures, Components A and B. Two sets of Hi-Lok fasteners are used to assemble the two substructures. The natural frequencies and mode shapes of the substructures are calculated using MSC Software packages. The mode shapes and natural frequencies of the test structure obtained from experimental modal analysis are compared to evaluate the accuracy of the proposed scheme.

Finite Element Modelling of Hi-Lok Fasteners

In this study, the 3D models of the components and the structure with Hi-Lok fasteners were developed using the CATIA V5 software package (CAD). The assembled structure consists of two components, Component A and Component B, joined together with Hi-Lok fasteners as shown in Figure 1(a). Each of the components has the same dimensions with a length of 295 mm, a width of 50 mm and a thickness of 6.3 mm. The material used for Component A and Component B is Aluminium 7075. The material properties of both components are listed in Table 1 and Table 2. In the previous study, the initial FE model for each component was updated using the FE model updating approach, which is in line with the procedure adopted by [20]-[27]. Before performing the FE modal analysis of the assembled components, the FE model updating technique was carried out to correct modelling of Components A and B. The material for the Hi-Lok pin and collar are Alloy Steel and Aluminium Alloy respectively and the material properties are listed in Table 3. The side view of the Hi-Lok fasteners is shown in Figure 1(b).



(a) (b)

Figure 1: (a) 3D CAD model of the assembled components with Hi-Lok fasteners, (b) side view of the Hi-Lok fasteners

Table 1: Material properties of Component A

Property	Nominal value	Updated value	Unit
Young's modulus	70,200	69,895.02	MPa
Poisson's ratio	0.3	0.384811	Unitless
Mass density	2.72×10^{-6}	2.71×10^{-6}	kg/mm^3

Table 2: Material properties of Component B

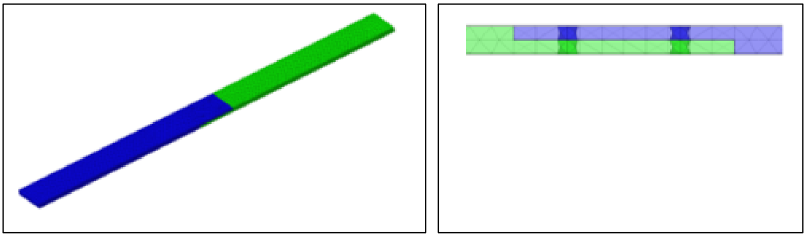
Property	Nominal value	Updated value	Unit
Young's modulus	70,200	69,902.26	MPa
Poisson's ratio	0.3	0.379136	Unitless
Mass density	2.72×10^{-6}	2.71×10^{-6}	kg/mm^3

Table 3: Nominal value of material properties of Hi-Lok fastener

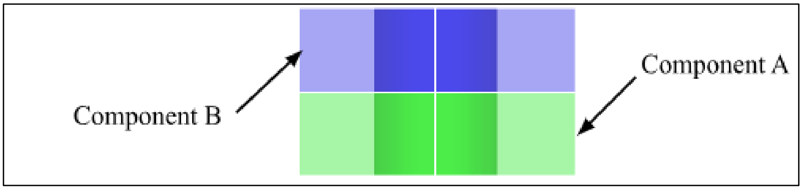
Property	Value	Unit
Young's modulus	190000	MPa
Poisson's ratio	0.3	Unitless
Mass density	7.85×10^{-6}	kg/mm^3

In this study, four different FE models of the structure with Hi-Lok fasteners were used. MSC PATRAN and NASTRAN were used to create and analyse the FE models. Models A to D are referred to as solid component Hi-Lok model, components without Hi-Lok model, hybrid component Hi-Lok model and simplified component Hi-Lok model, respectively. The element size of 5 mm was used to create FE models with 3D or 2D elements after a series of convergence tests were performed. The first 5 natural frequencies and mode shapes were calculated using the MSC NASTRAN SOL 103 normal modes analysis.

Model A, the solid component without Hi-Lok model consists of 4-noded tetrahedral elements in 3D solid meshes for the components (Figure 2). For the components with Hi-Lok models or Model B, the solid components and Hi-Lok models consist of 4-noded tetrahedral elements in 3D solid meshes (Figure 3). The 1D element BAR, which was used to represent the connection between Component A and Component B in the hybrid component Hi-Lok models (Model C), was replaced by the representation of the Hi-Lok pins and collars in Model A (Figure 4). In the simplified Hi-Lok model (Model D), the components were modelled with 4-noded, quadrilateral shell elements. The representation of the Hi-Lok pins and collars in Model D was carried out with 1D element BAR, the two ends were then connected with RBE2 elements (Figure 5).

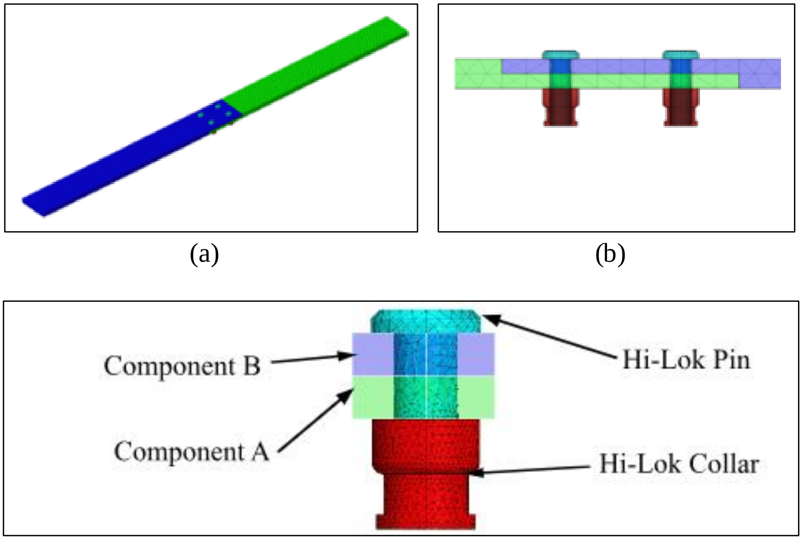


(a) (b)



(c)

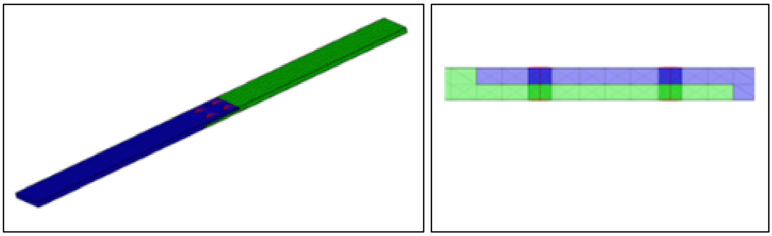
Figure 2: (a) FE model of the components without Hi-Lok model (Model A), (b) cross-section at the Hi-Lok fasteners of Model A, (c) close-up view of the Hi-Lok fasteners of Model A



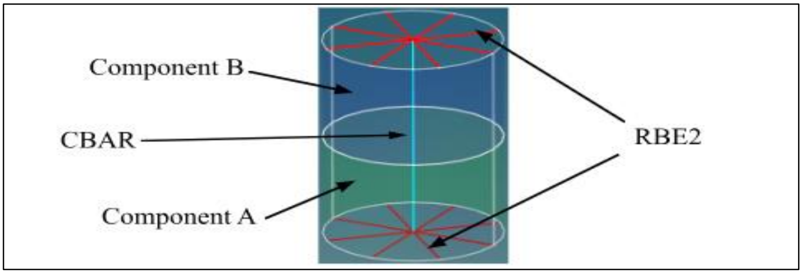
(a) (b)

(c)

Figure 3: (a) FE model of the solid components - Hi-Lok model (Model B), (b) meshing at the Hi-Lok fasteners of Model B, (c) close-up view of the Hi-Lok fasteners of Model B

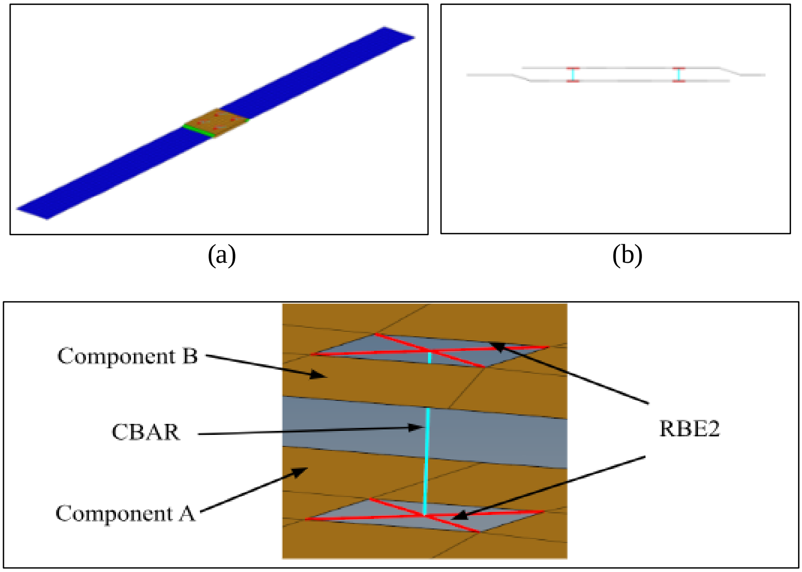


(a) (b)



(c)

Figure 4: (a) FE model of the hybrid component - Hi-Lok model (Model C), (b) cross-section at the Hi-Lok fasteners of Model C, (c) close-up view of the Hi-Lok fasteners of Model C


(a)

(b)

(c)

Figure 5: (a) FE model of the simplified component- Hi-Lok model (Model D), (b) meshing at the Hi-Lok fasteners of Model D, (c) close-up view of the Hi-Lok fasteners of Model D

Table 4: Detailed information on the four FE models of Hi-Lok fasteners

Detail	Model A	Model B	Model C	Model D
Type of element (Components A and B)	3D CTETRA4	3D CTETRA4	3D CTETRA4	2D CQUAD4
Type of element (Hi-Lok)	None	3D CTETRA4	1D RBE2-CBAR	1D RBE2-CBAR
Number of elements	14642	451507	19654	1214
Number of nodes	3869	96091	4990	1361

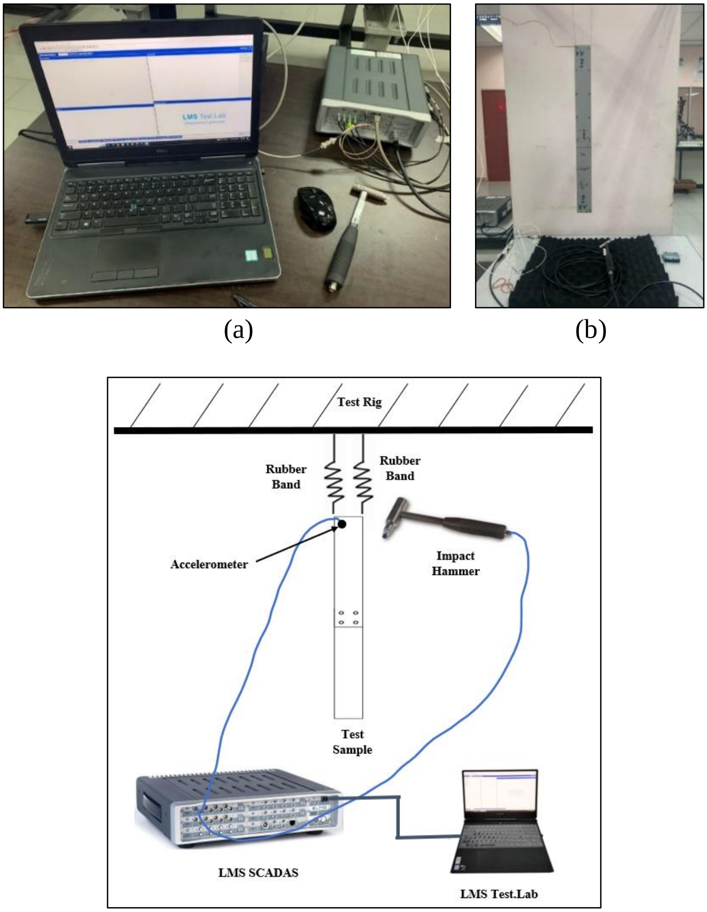
Experimental Modal Analysis of the Test Structure

Experimental investigations usually provide important insights to better understand the dynamic behaviour of assembled structures [6], [15]. In this study, the test structure under investigation was an assembled structure consisting of two identical Aluminium 7075 components connected with Alloy Steel Hi-Lok pins and Aluminium Alloy Hi-Lok collars. EMA was performed on both components A and B and on the assembled structure to measure their mode shapes and natural frequencies. The equipment used for the experiment: LMS Test.Lab, LMS system, the accelerometer and the impact hammer are shown in Figure 6(a). The EMA setup for the assembled structure is shown in Figure 6(b). The assembled structure was suspended from a test rig with rubber bands to simulate free-free boundary conditions. The schematic representation of the whole system configuration for impact testing is shown in Figure 6(c).

Results and Discussion

The objective of this study was to propose a modelling scheme for the analysis of the dynamic behaviour of an assembled structure with Hi-Lok fasteners. The results of this paper were obtained using the FE models and experiments presented in the previous sections. The natural frequencies and mode shapes were calculated using MSC NASTRAN SOL 103 and measured using impact hammer testing under free-free boundary conditions. For the development of the modelling scheme, the EMA results were used as a reference. More specifically, four different FE models were created using thorough, comprehensive descriptions of the test structure that was the subject of the study. The model that is able to accurately represent the test structure with the lowest total error and computational time is the most appropriate modelling scheme.

Four different capabilities of accurately predicting natural frequencies were obtained depending on the FE models (Table 5). Direct comparison of the natural frequencies of the FE models showed that Model D had the lowest total percentage error (3.4%), computational time and memory disk usage among all models, making it the most accurate and effective model for representing the test structure in five modes. This achievement shows the ability of Model D to adequately represent the mechanisms of the Hi-Loks with a small number of degrees of freedom using 1D elements.



(a) (b)

(c)

Figure 6: (a) Testing equipment for EMA, (b) experimental setup of the assembled structure with Hi-Lok fasteners, and (c) overall system configuration for impact testing

On the other hand, Model A had the highest total error of 384.6%, considering that the Hi-Loks fasteners were not included in the modelling.

Model B appears to have had the highest computational time and memory disk usage as the Hi-Loks and the components were modelled with 3D elements, which increased the number of degrees of freedom. Another observation from the direct comparison was that model C also had the highest correlation despite the use of 3D elements, which means that model C is the best at predicting the natural frequencies compared to the other 3D FE models.

The results show that the use of 1D elements to model the Hi-Loks can correlate better with the test structure than the use of 3D elements, as shown by model B. The results of the direct comparison show that the use of 1D elements and 2D elements in Model D can correlate better with the test structure compared to the other three FE models. Therefore, the proposed scheme can be useful for researchers and engineers who want to develop and analyse the dynamic characteristics of FE models of aircraft structures with a large number of Hi-Lok fasteners efficiently and more accurately.

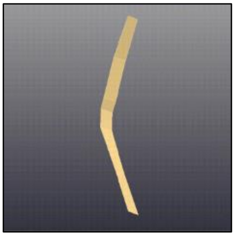
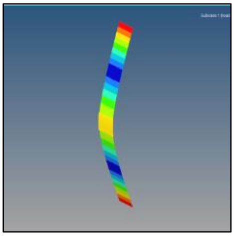
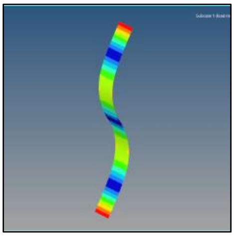
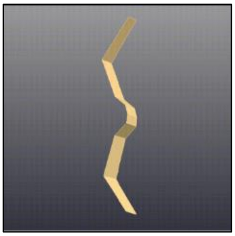
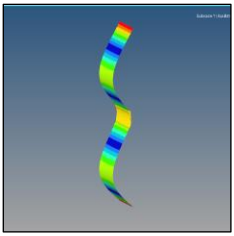
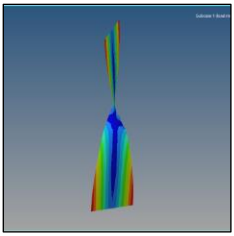
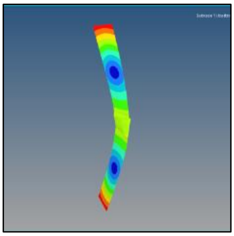
Modal Assurance Criterion (MAC) values between 0 and 1 indicate the degree of correlation of the mode shapes between the EMA and the FE model. In this study, the MAC values from the MAC analysis of the EMA and Model D were between 0.65 and 0.98 (Table 6). These results show that the mode shapes of EMA and Model D have a very good correlation, with the exception of the fifth mode. The MAC value for the fifth mode was 0.65, suggesting that other excitation techniques such as hitting the test structure in the other directions, may be necessary to improve the quality. Furthermore, the fifth mode was found to be an in-plane mode compared to the other modes (out-plane mode). However, the overall results in terms of natural frequencies and mode shapes show that Model D is the best modelling approach for the dynamic behaviour of the assembled structure with Hi-Lok fasteners.

Eight different convergence tests with different element sizes were carried out for Model C (Figure 7). The aim of these convergence tests was to evaluate the accuracy of the prediction of Model C in relation to the element sizes used. It was found that the smaller the size, the more accurate the prediction for all modes in this study. In other words, to increase the prediction accuracy of Model C based on 3D element modelling, the element size 1 mm should be used instead of the other sizes. It was found that using the 1 mm element size led to a drastic reduction in the total error by about 93%. However, this reduction led to an enormous number of degrees of freedom (DOFs) in Model C with 988818 DOFs (Table 7), resulting in an enormous size of the matrices for the eigensolutions. These results show that Model C with an element size of 1 mm definitely does not seem to be a good choice for this study, but this model may be of interest to researchers dealing with stress analysis or fatigue analysis. However, it is important to maintain a balance. While models with smaller elements improve accuracy, they also increase computational costs, so the element size must be optimised to keep accuracy within acceptable computational limits. Therefore, an element size of 5 mm was chosen for this study as it is the most efficient and time-saving.

Table 5: Comparison of EMA and FE modal analysis of Model A, Model B, Model C and Model D

Mode	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	EMA (Hz)	**FE Model A (Hz)**	**Discrepancy between 1 and 2 (%)**	**FE Model B (Hz)**	**Discrepancy between 1 and 4 (%)**	**FE Model C (Hz)**	**Discrepancy between 1 and 6 (%)**	**FE Model D (Hz)**	**Discrepancy between 1 and 8 (%)**
1	86.4	187.828	117.3	155.901	80.4	130.888	51.4	86.572	0.2
2	303.3	542.898	79.0	429.882	41.7	420.344	38.6	304.579	0.4
3	531.8	883.495	66.1	831.532	56.4	695.152	30.7	535.435	0.7
4	629.4	1010.933	60.6	863.792	37.2	754.723	19.9	630.166	0.1
5	775.1	1252.126	61.5	1022.157	31.9	941.118	21.4	759.689	2.0
Total Error (%)			384.6		247.6		162.1		3.4
Number of Nodes		3869		96091		4990		1361	
CPU Time Elapsed (s)		7		353		10		3	
Memory Used (MB)		1500		5696		2800		1500	

Table 6: Comparison of the mode shapes between the EMA (left) and FE (right) models with MAC values

Mode	EMA Mode Shape	FE Mode Shape	MAC
1			0.92
2			0.98
3			0.85
4			0.95
5			0.65

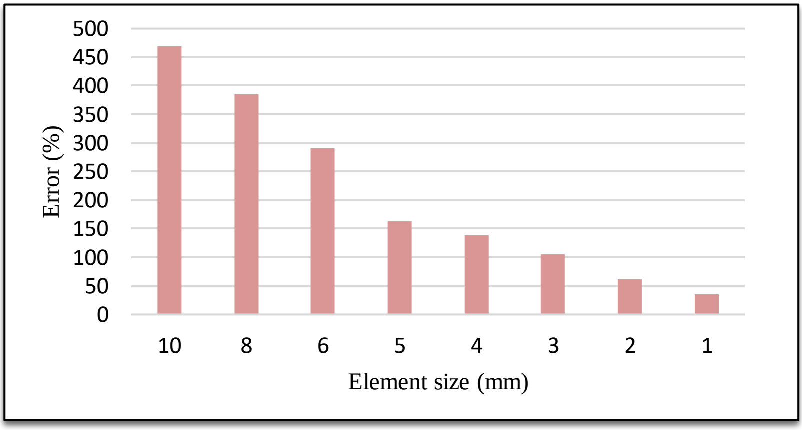


Figure 7: Convergence test on Model C

Table 7: Detailed information on Model C

Element size (mm)	Error (%)	Number of nodes	Number of DOFs
10	469.184	1004	6024
8	384.206	1418	8508
6	290.199	2704	16224
5	162.068	4990	29940
4	137.577	6667	40002
3	104.402	12812	76872
2	61.314	32900	197400
1	34.476	164803	988818

Conclusions

In this study, the investigation of the dynamic behaviour of an assembled structure with Hi-Lok fasteners is presented. Four different FE models were developed, analysed and evaluated against the EMA results to determine the ability of each model to accurately and economically represent the dynamic behaviour of the test structure. Model D, which was developed using 1D elements to represent the Hi-Loks and 2D elements for the beams, provides the best accuracy (96.6%) in representing the dynamic behaviour of the test structure and has the shortest computational time (3 seconds) and the lowest memory requirement (1500 MB) compared to the other three FE models. With this great performance demonstrated by the proposed scheme, researchers and engineers may develop and analyse the dynamic behaviour of FE models of aircraft structures with a large number of Hi-Lok fasteners in a very efficient and accurate way.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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