Influence of number of studs on compliance of a flight intersection joint

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Abstract: Flight intersection joints are temporary joints used to integrate one airframe section with another. They are characterized by their capacity to resist the rotational flexibility when subjected to an external bending moment, commonly termed as the joint rotational compliance (JRC). Currently, JRC is quantified mostly by extensive experiments on the flight intersection joints. The influence of number of studs in a stud-pocket type intersection joint on JRC is not yet well understood in literature which is addressed in this paper through numerical simulations. The variation in joint compliance and its dependence on number of studs are brought out through the analysis of circumferential distribution of joint displacement, JRC and joint rotational stiffness.

1. Introduction

Slender flights vehicles are made up of separate airframe sections as shown in Figure 1, upon assembly of airborne subsystems within the individual sections, they are joined together using a class of intersection joint. There are different types of flight intersection joints \[1-9\]. The selection of a type of joint depends on the joint compliance to be achieved, ease of integration, and requirement of a minimal occupied volume. A flight intersection joint (FIJ) is characterized by its resistance to the rotational flexibility when subjected to an external bending moment. This is called as the joint rotational compliance (JRC) and expressed in rad/Nm. This JRC helps in modelling the structure of the flight vehicle as a flexural beam with rotational springs at joints, to predict the natural structural mode shape and modal frequencies.

The JRC is often quantified through extensive experiments and sometimes through empirical relations whose accuracies are always questionable. A stud-nut-slot type of intersection joint which is conformal with cylindrical airframe geometry as shown in Figure 1 is quite popular. Several researchers have investigated the performance of flight intersection joints through numerical and experimental methods \[1-13\]. Kaplan \[10\] has determined the flexibility coefficients i.e. a measure of joint rotational stiffness (JRS, an inverse of JRC is another form of representation) for flight structural joint assemblies and reported the challenges in experimental and theoretical determination of the flexibility coefficients and the importance of these values in flight dynamics. Kumar \textit{et al.} \[11\] and Gunda and Krishna \[12\] conducted ground resonance test and predicted the free vibration response of the launch vehicles through finite element method (FEA) using beam elements representing the airframes and rotational spring elements representing the FIJs. They observed significant discrepancies in the predictions as
compared to the experimental data caused by the assumption of JRC values adopted in FEA and stressed upon the need for an accurate quantification of joint flexibility or the stiffness of the FIJs.

Alley and Gerringer [4] and Leadbetter et al. [5] investigated the prediction and measurement of natural vibrations on multi stage launch vehicles where they conducted experimental measurements of free vibration response of launch vehicles and observed considerable difference with the predicted vibration responses. They reported that invariably, computed mode data on launch vehicles which disregard local influences at FIJs will result in frequencies higher than actual; therefore, any reasonable approximation to stiffness of FIJ will move the computed results close to reality. Therefore, Alley and Leadbetter [3] provided a guide to joint evaluation which should provide a simple means for approximating the JRCs in a typical launch vehicle through an empirical relation. But this is based on 12 experiments and its accuracy is uncertain for different diameters and type of FIJs.

The behaviour of FIJs are also modelled using analytical approaches similar to that presented by Wojnar et al [13] for the tubular flange joints. Further the researchers have studied the joint compliances experimentally and stressed the importance of JRC in predicting the dynamic response of a flight vehicle. Although the importance of JRC in a FIJ and its experimental determination are well elaborated, prediction of JRC through numerical methods is not attempted. This paper presents the influence of number of studs on compliance using finite element analysis code ANSYS Workbench [14]. The details of numerical modelling, evaluation of joint opening and computation of JRC are discussed in the paper.

2. Numerical modelling and analysis

The geometry and dimensions of a typical stud-nut type of a flight intersection joint considered in this study is shown in Figure 2 with 8 numbers of M10 studs. The section airframes are made of aluminium alloy with elastic modulus $E = 70$ GPa and Poisson’s ratio $\nu = 0.32$. The stud and nut are made of high strength alloy steel with $E = 200$ GPa and $\nu = 0.3$. The entire geometry is discretised with 20 node hexahedral element with an element size of minimum 1 mm as shown in Figure 3(a). The interface between the external cylindrical surface of stud with 1) receiving internal threaded hole surface in front bulkhead of Section-2 airframe, and 2) inner threaded surface of nut are established with bonded contact to simulate the screwed joint as shown in Figure 3(b).
Figure 2: Details of a stud-pocket type flight intersection joint connecting airframe Sections-1 and 2

Frictional contacts with a friction coefficient of 0.5 is established between 1) the butting surface of nut against the flat vertical face in the slot of rear bulkhead in Section-1 airframe; and 2) the two contacting flat end surfaces of both the bulkheads.

(a) FEA model
A pretension of 20000N [15] is applied on the threaded surface of stud and an equivalent compressive force is applied on the flat butting surface of nut on the stud-pocket to simulate the effect of pre-tightening torque of 40 Nm. First yield bending moment $M_y$ is calculated for the geometry of airframe and the external bending moment $M$ is proportionally applied in steps until $M_y$ capacity is reached. The FE model with boundary conditions is shown in Figure 3(a). The axial displacements are measured from the analysis results. The joint compliance and the opening is evaluated to find the variation of JRC and its dependence on the number of studs.

3. Results and discussions

The distribution of axial displacement $u_x$ around the circumference of the joint in degrees with $0^\circ$ starting from the left reference orientation of the airframe through the top reference ($90^\circ$), the right reference ($180^\circ$) and the bottom reference ($270^\circ$) to the starting reference is shown in Figure 4. From Figure 4 and 5, it can be inferred that the maximum axial opening of the joint is 9.5 mm at $90^\circ$ for 4 number of M10 studs. The opening reduces to 4.5 mm by increasing the number of studs from 4 to 6 numbers. The opening remains almost same for the joint with 8 and 10 number of studs. Enhancing the number of studs to 12 numbers reduced the opening by 2.5 mm. Further, it can be found that the joint openings are almost zero exactly at all stud locations. The bottom segment of the joint from $180^\circ$ to $360^\circ$ experiences a compressive action due to the hogging moment applied at the joint, tends to close the joint further and experiences almost zero opening. The joint’s axial openings at RT are increasing linearly with increase in $M / M_y$ and reaches maximum at $M / M_y = 1$ as seen in Figure 5.

The opening slope $\theta$ is calculated based on axial displacement with respect to neutral axis using airframe geometry. The JRC is calculated as ratio of $\theta / M$ in rad/Nm. The inverse of JRC is the joint rotational stiffness called as JRS. A combined plot showing JRC, JRS and maximum axial opening as a function of number of studs is shown in Figure 6. The JRC reduces from 1.3 to 0.35 rad/MNm, JRS increases from 0.7 to 2.85 MN/rad and the axial opening reduces from 9.5 mm to 2.4 mm as the number of studs are increased from 4 to 12. Although there is no appreciable difference noticed between 8 and 10 numbers of M10 studs on all three parameters studied here, the 12 number of studs provides least joint compliance with highest rotational stiffness in this stud-nut type of flight intersection joint.
Figure 4: Axial opening along circumference starting from RL at $M/M_y = 1$ for varying number of M10 studs

Figure 5: Variation of axial deformation at RT with applied moment for varying number of studs
4. Conclusion

The flight airframe sections are joined to one another through a typical stud-nut type of intersection joint. This joint is characterized by the value of its joint rotational compliance, JRC. A joint need to exhibit a least JRC to simulate a flight structure with minimal flexibility at temporary joints and to have a continuity in natural mode shapes without an appreciable slope change. This paper numerically investigated the influence of number of studs on joint compliance and shown that a stud-nut type of joint with 8 to 12 numbers of M10 studs exhibited good performance in terms of JRC and JRS. The decrease in JRC is very significant from 4 to 8 number of studs. It is recommended to have 12 number of M10 studs to achieve a least joint rotational compliance.

5. References

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