Predicting the Rotational Compliance of a Flight Inter-section 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 inherent capacity to resist the rotational flexibility when subjected to an external bending moment, commonly termed as the joint rotational compliance (JRC). They are quantified mostly by extensive experiments. This paper presents the details of 1) numerical modelling and analysis of a cylindrically conformal stud-nut-slot type of a flight intersection joint, 2) prediction of the circumferential distribution of joint flexibility and 3) computation of JRC. Further, it highlights the effect of pre-tightening on JRC and suggests few adoptable methods to enhance the JRC.

Keywords: *Flight intersection joint (FIJ), joint rotational compliance (JRC), joint rotational stiffness (JRS), finite element analysis (FEA), pre-tightening.*

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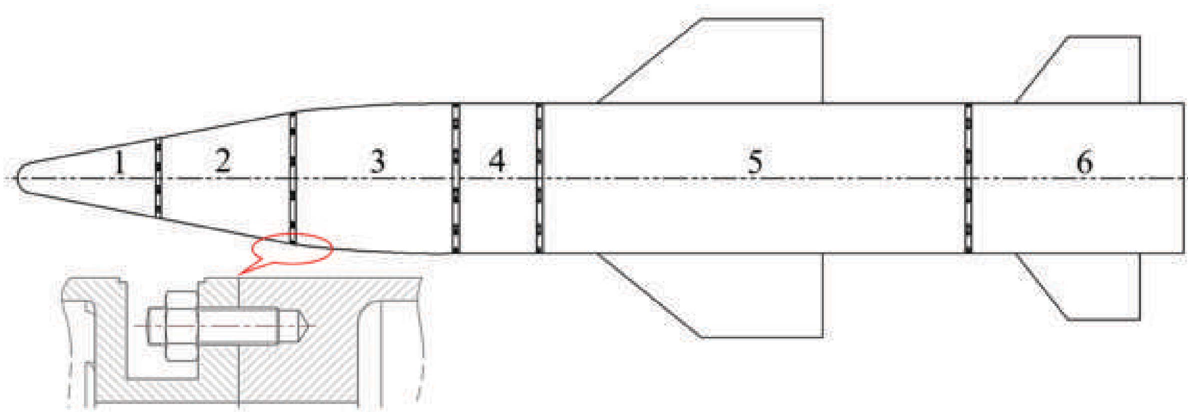
Introduction

Slender flights such as launch vehicles are made up of separate and individual cylindrical (few with conical or ogive) airframe shell type of sections as showed in Figure-1. After assembly of airborne subsystems within the individual airframe sections, they are joined together using an intersection joint which is an integral feature provided at the ends of each airframe section. There are several types of flight intersection joints (Maloney et al., 1970 and 1971). The selection of a particular type of joint depends on the joint compliance to be achieved, ease of integration, and the requirement for a minimal occupied volume. Mostly, the FIJs are temporary joints which can be opened or fastened on need. Only in certain uncommon cases, to meet the manufacturing and integration constraints, the airframe structural sections are made separately and then joined at intersections either permanently by welding or semi-permanently by riveting (Maloney et al., 1970 and 1971). The flight intersection joints experience more challenging requirements when compared to other bolted joints used within the flight vehicle, as well as in other engineering applications as they are exposed to more harsh environments and loadings during the flight and transportation. A flight intersection joint is characterized by its resistance to the rotational flexibility when subjected to an external bending moment arising out of flight loads coming from inertia, propulsion and aerodynamics. This rotational flexibility at the joint is called as a joint rotational compliance 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 (Gunda, J.B., 2014), in order to predict the natural structural mode shape and modal frequencies. This is often quantified through extensive experiments and sometimes through empirical relations whose accuracies are always questionable. A stud-nut-slot type of intersection joint (Maloney et al., 1970) which is conformal with cylindrical airframe geometry as showed in Figure-1 is quite popular.

Figure-1: Typical flight vehicle with five intersection joints connecting six airframe sections



Although there are several types of flight intersection joints, their engineering design, constructional details and concepts are different from each other (Maloney et al., 1970; Hillmer, 1963; Lasker et al., 1974; Gharouni et al., 2014). But their loadings and method of prediction of joint stiffness can be closely related to the mechanics of bolted circular flange joints adopted in tubular structures, which are commonly found in general engineering applications. Significant research has been carried out for many years on bolted circular flange joints in tubular structures and different methods for the design of these joints have been developed (Rockey and Griffiths, 1970; BSC, 1974; BS8100, 1988; Stelco, 1981; Igarashi et al., 1985 and 1987; Kato and Hirose, 1984; CIDECT13, 1984; Packer and Henderson, 1992; Cao and Bell, 1984, 1996a,b and 1997; Stamatopoulos and Ermopoulos, 2008; Couchaux et al., 2010 and 2011; Wojnar and Kozłowski, 2006; Kozlowski et al., 2007; Kozłowski and Wojnar, 2008; Azim, 2013; and Emara, 2019). On the other hand, comparatively, the quantum of research on FIJs is very less and only limited knowledge is available in open literature. The design of FIJs relied more on meeting functional and stiffness requirements based on elaborate experiments and limited theoretical studies. But the well-established concepts and the method of analysis of bolted circular flange joints in tubular structures can be extended to develop both the theoretical models and numerical analysis of FIJs.

Kaplan (1971) 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 et al. (2013) and Gunda and Krishna (2014) conducted ground resonance test and predicted the free vibration response of the launch vehicles through 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.

Although the importance of JRC in a FIJ and its experimental determination are well elaborated, prediction of JRC through numerical methods is not attempted. Therefore, this paper is intended to bring out a numerical method based on finite element analysis (FEA) to predict the JRC in FIJs. The details of numerical modelling of FIJ joint, method of extracting the joint rotational flexibility and computation of JRC are discussed. Furthermore, the effect of pre-tightening force applied to the studs in the FIJ on JRC; and few practical methods to enhance the JRC are investigated in this paper.

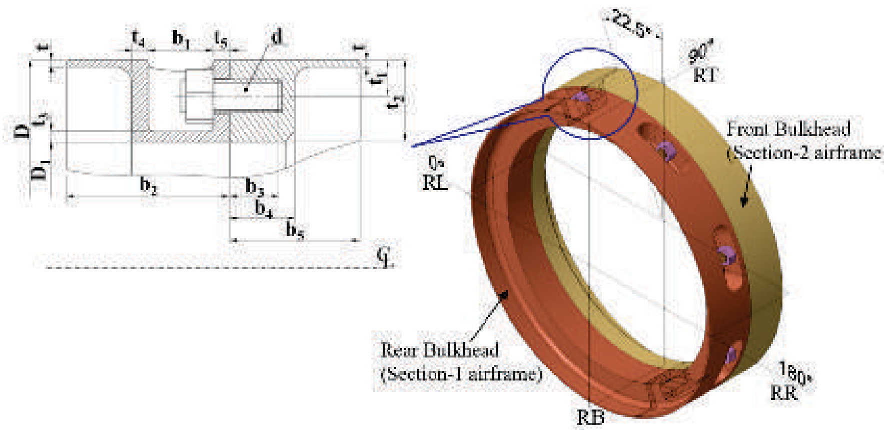
Numerical Simulation of JRC of FIJ

The material model, the numerical modelling approach and analysis are presented in this section.

Geometry and Material

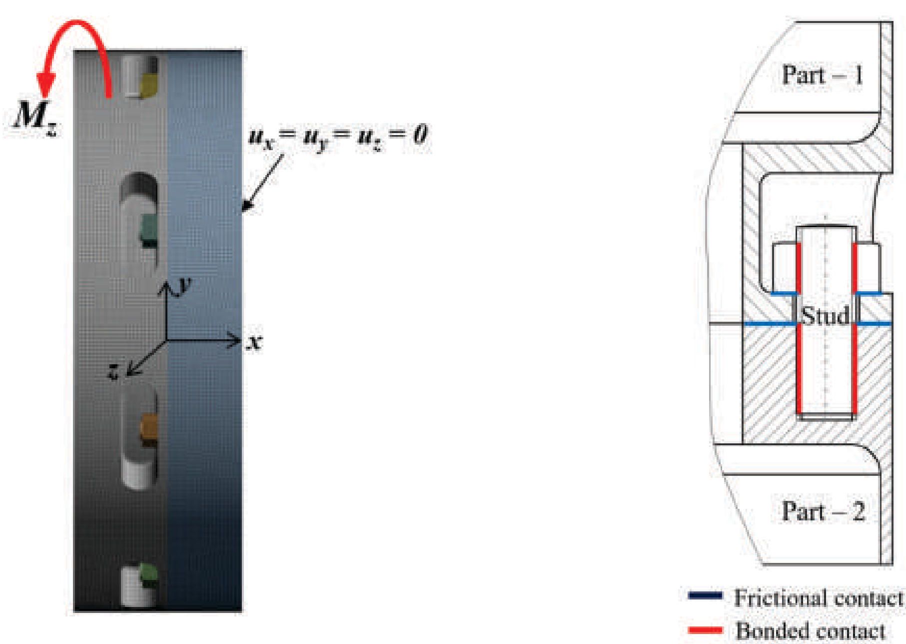
A stud-nut-slot type of intersection joint which is conformal to the cylindrical airframe geometry, showed in Figure-1 is provided with a number of studs screwed at equi-angular distance on the front bulkhead of the Section-2 airframe. The studs in the front bulkhead of Section-2 airframe can enter into the respective holes and slots in the rear bulkhead of Section-1 airframe and are tightened with nuts as showed in Figure-2. The FIJ considered for the present study is typically for an airframe diameter D = 300 mm and shell thickness t = 2 mm, featured with 8 numbers of M10 studs. All dimensions represented symbolically in Figure-2 in the stud-nut-slot feature in both the airframe sections can be expressed in terms of the stud nominal diameter. The reference nomenclatures such as RL, RR, RT and RB showed in Figure-2 respectively refer to the references at left, right, top and bottom locations in FIJ where RL is taken at $\theta = 0$. The airframe joints are made of aluminium alloy with elastic modulus E = 70 GPa and Poisson's ratio ν = 0.32. The stud and nut are made of EN24 steel with E = 200 GPa and ν = 0.3. These are adopted in the linear elastic, moment-controlled analysis in FEA code (ANSYS, 2019).

Figure-2: Details of a stud-nut-slot type FIJ connecting airframe sections-1 and 2



Numerical Model for FEA

The entire geometry of FIJ showed in Figure-2 is discretised using 20 node hexahedral elements with an element size of minimum 1 mm as showed in Figure-3(a). The interface between the external surface of stud and inner tapped hole surface of front bulkhead in Section-1 and inner surface of nut are modelled with bonded contact to simulate the screwed joint as showed in red colour in Figure-3(b). 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 pocket of rear bulkhead in Section-1; and 2) the two contacting flat end surfaces of both the bulkheads showed in blue colour in Figure-3(b). All nodal degrees of freedom at the end surface of front bulkhead in Section-2 airframe are constrained.



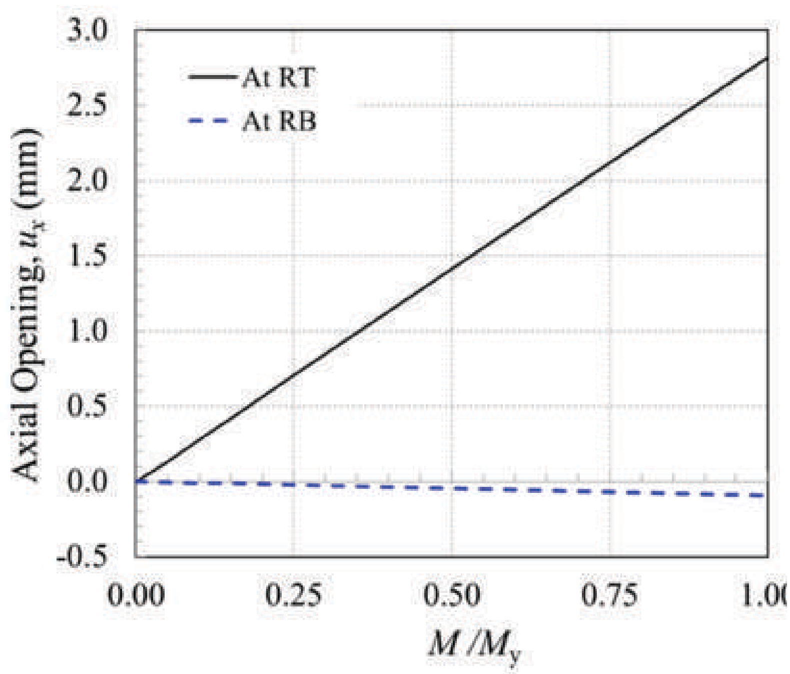
(a) FE model with loading and boundary conditions

(b) Contact details

Simulation and Computation of JRC

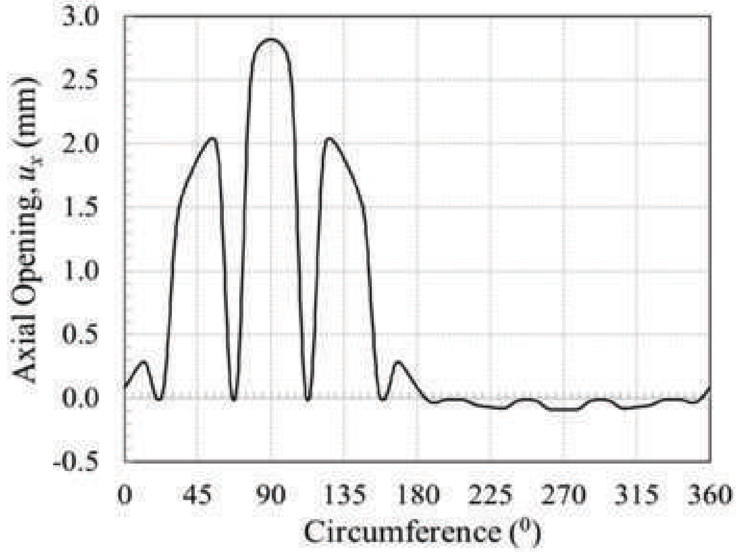
Airframe materials first yield bending moment M_y is calculated for the geometry of bulkhead and the bending moment M is proportionally applied at left end of rear bulkhead in Section-1 airframe, in steps until is M_y reached. The axial displacements between the two butting surfaces of bulkheads in the FIJ are measured at the end of every load step in the analysis. The variation of axial displacement in the joint i.e., *w.r.t.* the ratio of bending moments (applied M normalised with M_y) at RT and RB is showed in Figure-4. A maximum opening of 2.65 mm is observed at RT location and 0.1 mm compression is observed at RB due to the nature of hogging moment applied.

Figure-4: Variation of axial deformation at RT and RB with applied moment



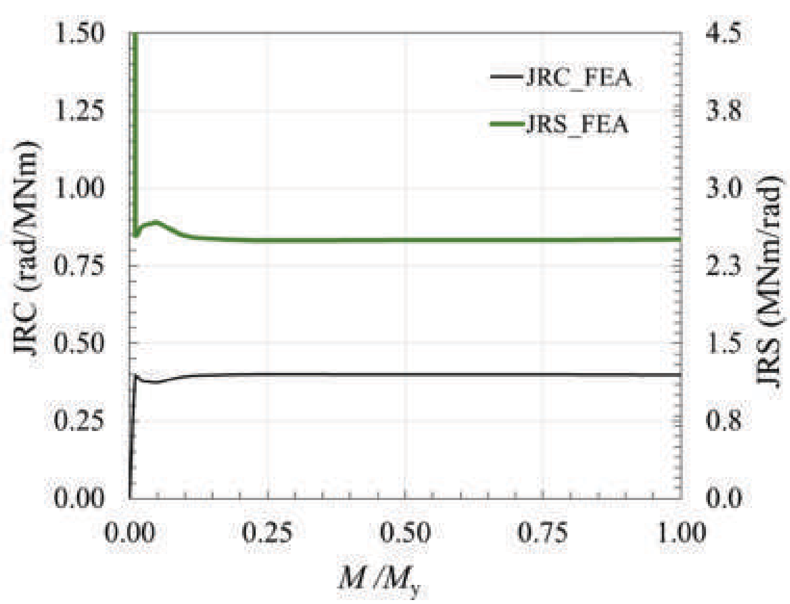
The variation of axial opening throughout the circumference of FIJ at the maximum applied moment of M_y, starting from 0° at RL, 90° at RT, 180° at RR and 270° at RB to 360° at RL references is showed in Figure-5. A maximum opening of 2.65 mm is observed at RT orientation. There is no axial opening at eight locations where the studs are introduced and tightened with nuts. From the RR to RL region, the joint undergoes compression of up to 0.10 mm at RB location.

Figure-5: Axial opening along circumference starting from RL at $M/M_y = 1$



The opening slope ϕ is calculated based on axial displacement with respect to bottom pivot at RB. The JRC is calculated as ratio of ϕ/M in rad/Nm. The inverse of JRC is the joint rotational stiffness called as JRS. The variation of JRC and JRS with the applied load is computed and plotted as showed in Figure-6. It can be observed that the JRC and JRS remain constant for a definite type of FIJ, are independent of any applied load, and qualify these parameters to be considered as joint property. These can be compared with experimental results. An ideal or a preferred joint should possess very less joint flexibility i.e. JRC and very high JRS.

Figure-6: Predicted JRS and JRC



Effect of Pre-tightening on JRC

The pre-tightening force which will be generated in the stud and nut while torqueing the studs are ignored in the simulations thus conducted. This pre-torqueing of studs while joining the FIJ generates tension in studs and equivalent compression in clamped surfaces, transferred through the nuts. Now, the FEA model for the numerical simulations capturing the realistic conditions is considered for the analysis. A pretension F_p = 20000 N (Bickford, 2008) is applied on the threaded surface of stud and an equivalent compressive force is applied on the butting surface of nut on the slot to simulate the effect of pre-tightening torque *T* = 40 Nm applied on the M10 stud-nut, as showed in Figure-7. The simulation performed earlier is repeated with the same moment control with the new model of FEA in ANSYS (2019). The JRC and JRS are computed following the same procedures as explained previously. The variation of axial opening and JRC with pretightening and without pretightening are studied. The percentage difference in the axial displacement of the joint, JRC and JRS between no-pretightening and with pretightening w.r.t. no-pretightening are calculated and are plotted as showed in Figure-8.

Figure-7: Model for FEA with pre-tightening

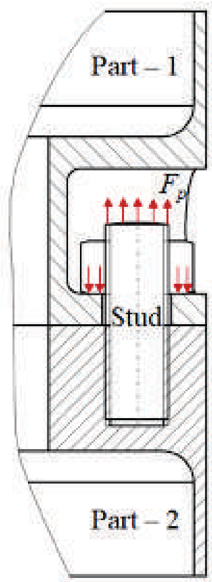
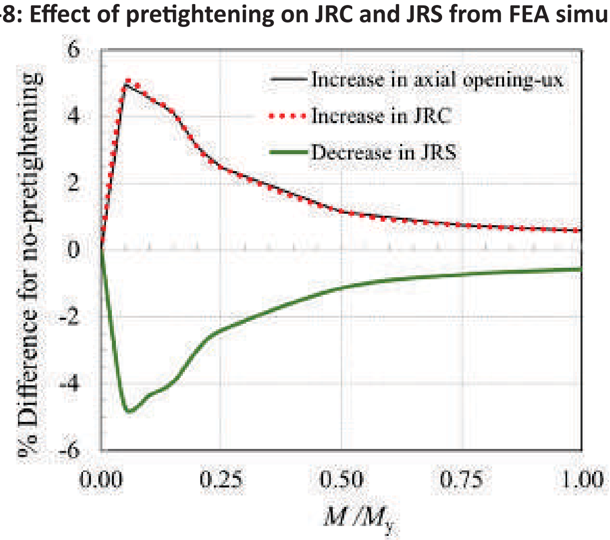


Figure-8: Effect of pretightening on JRC and JRS from FEA simulations



It can be found that there is no much variation with and without pretightening. The differences are around 5% only. The effect of considering the pre-tension in the studs appears to be insignificant for the joint compliance. But it is not advisable to clamp the joint without pre-tightening because the pre-tightening ensures proper clamping between the two airframe sections. It ensures and retains the joint compliance and prevents the loosening of the joint during the service life of the flight where the joint can experience flight, handling, transportation and articulation loads.

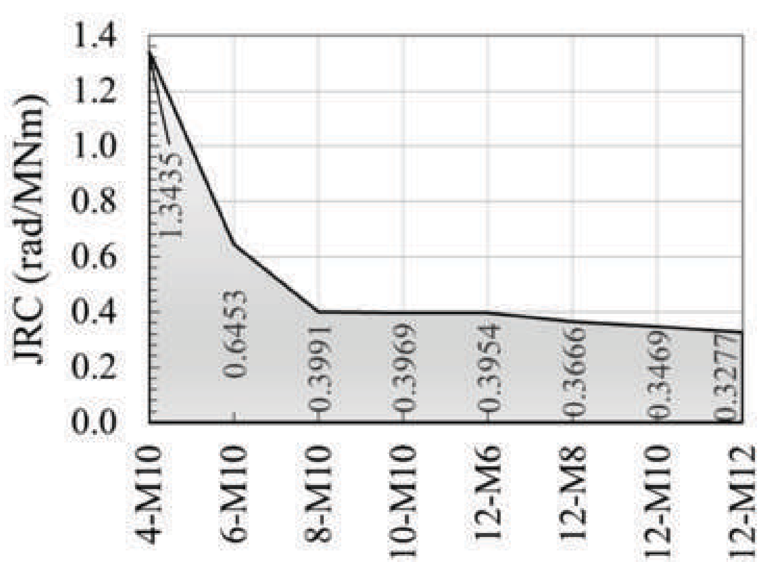
Studies to Enhance JRC

Studies were conducted to explore the practical methods of achieving minimal JRC during the initial design stage itself. One method is to investigate the effect of number of studs for the given nominal size of the stud in the FIJ and the second method is to examine the effect of size of studs for the given number of studs.

Variation in Number of Studs

Eight numbers of M10 studs are adopted in the studies thus discussed. Effect of variation in the number of studs on JRC and JRS is explored for the given metric size of studs and the airframe diameter as showed in Figures-9 and 10. There is a 50% reduction in JRC for the joint having six number of M10 studs when compared to the joint with four number of studs. A reduction in JRC of 38.5% is achieved with eight number of studs as compared to that with six number of studs. There is no much variation observed in JRC from eight to twelve numbers of studs. Therefore, for the example airframe diameter of 300 mm, adopting eight numbers of M10 studs proves to be an optimum solution to achieve a minimum possible JRC and maximum JRS.

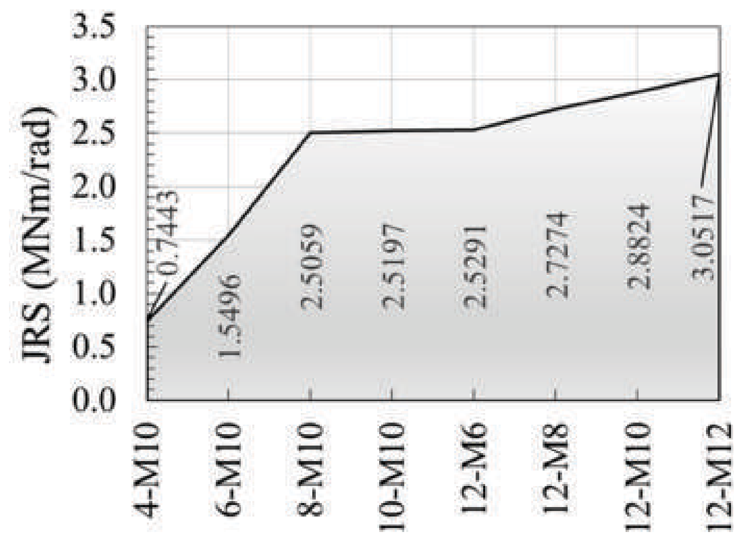
Figure-9: JRC variation w.r.t. no. of studs and size of studs



Variation in Size of Studs

The effect of variation in metric size of studs for the given number of studs and the airframe diameter is explored and the results are as showed in Figures-9 and 10. Twelve numbers of studs are considered for the joint and the size of stud is varied from M6 to M12. It is observed that the number of studs has a major influence on the JRC in addition to the metric size of studs. However, it can be found from the numerical simulations that the JRC is decreased very marginally when the stud size in the joint is changed from M6 to M12. On the other hand, twelve numbers of M6 studs prove to be much more effective in improving the joint stiffness as compared to eight numbers of M10 studs.

Figure-10: JRS variation w.r.t. no. of studs and size of studs



Results and Discussions

A flight intersection joint is characterised by the value of its JRC which inherently represents the resistance offered by the intersection joint against unit rotation under an externally applied bending moment. Numerical modelling and simulation of the joint for estimating and minimising the JRC of stud-nut-slot type of FIJ is evolved and assessed. Numerical analysis of the FIJ provides a maximum opening of 2.65 mm at RT orientation. Whereas no axial opening is observed at the stud locations. From the RR to RL region, the joint undergoes compression of up to 0.1 mm at RB zone. The effect of applying pre-tightening appears to cause only less than 5% variation on the predicted JRC or JRS value of FIJ. But there are a number of merits when pre-tightening is applied in the FIJ as it prevents vibration loosening of the joint. Even increasing the maximum possible number of studs within a given airframe diameter is found to be more effective in reducing the JRC value, more than the size of studs. A 52% reduction in JRC is found for the joint having six studs compared to four M10 studs. The JRC is further reduced by 38.2% for the joint with eight studs compared to that with six numbers of M10 studs. Only about 0.5% reduction is found for the joint having 8 and 10 numbers of M10 studs. About 17.1% improvement is observed between the joint with 12 numbers of studs with size of studs varying between M6 to M12.

Conclusions

Flight intersection joints play an important role in ensuring the structural integrity of the full flight vehicle. This paper presented the details of numerical modelling approach in numerical simulation of a typical flight intersection joint and computation of JRC or JRS. The effect of pretightening of studs on JRC of the FIJ is explored. It is found that the influence of pre-tightening is within 5% on the computed JRC. However, pre-tightening is essential to maintain the JRC against vibration loosening. Further, the influence of number of given metric size of studs and the size of studs for the given number of studs were explored. It is found that more number of studs with lesser metric size performs better in JRC values when compared with less number of studs of higher metric size.

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