Evaluation of Fastener Stiffness Modelling Methods for Aircraft Structural Joints

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Abstract. An investigation has been made to predict the accurate fastener stiffness for the Aircraft metallic joints that can be used in Finite element models to simulate realistic behaviour. There exist several semi empirical equations like Tate & Rosenfeld (1946), Huth-Schwarmann (1986), Swift (1971) & Grumman (1983) etc. that can be used to calculate the shear and stiffness of fasteners. However the stiffness calculated varies for each of these methods and eventually leading to varying load distribution. In this paper a parametric study has been conducted to identify the most accurate method to identify the fastener stiffness. The relevant shear stiffness calculated adds certain flexibility to fasteners and peak loads tend to distribute across all the fasteners matching with the real scenario.

INTRODUCTION

In Aero structures typically Metallic fittings are conservatively sized as their weight is usually small relative to their purpose. Hence during PDR (Preliminary design review) and CDR (Critical design review) cycles, fasteners are modelled in finite element analysis using high stiffness due to ease of modelling, to attain quick results and to have purposefully conservative high margins. So that inadvertently if loads get increased, the designed fittings would be still capable of managing the increased loads without failure, this typical approach is commonly followed which leads to oversized heavy weight fittings.

Nevertheless these fittings enter into service after aircraft certification and in this situation if there are any non-conformances (MRBE issues), e.g., a thinned flange or oversized hole due to excess machining then using the high fastener stiffness in finite element analysis may lead to negative margins which in turn results in scraping the expensive fitting or retrofitting, increasing the overall weight. This is an expensive request as material, time and effort gets unnecessarily wasted. To avoid this kind of situation there exist several semi empirical equations to that can be used to calculate the relevant fastener shear stiffness of the fasteners notable the following:

- Tate & Rosenfeld (1946)
- Huth-Schwarmann (1986)
- Swift (1971)-Douglas aircraft company
- Grumman (1983)-Northrop Grumann

The stiffness calculated from above semi empirical equations add certain flexibility to fasteners and peak loads tend to distribute across all the fasteners matching with the real scenario. Test specimen results are illustrated (Fig.1) [1].

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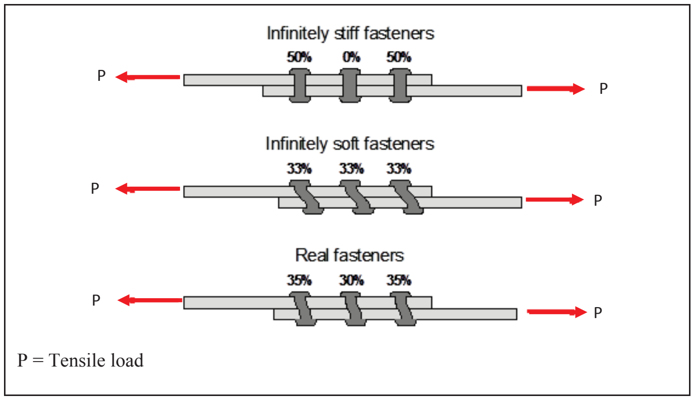

Figure 1. Fastener Flexibility based on its Stiffness

In this paper, parametric study of a simple single shear lap joint with 2 rows of 3 fasteners in series along the loading direction is considered. Analysis is performed on FE model (six iterations as shown below). In each FE iterations, fasteners stiffness is calculated using different empirical equations as listed (Table 1).

TABLE 1. FEM Iterations

Iteration No	Empirical Equation
Iteration 1	High Shear Stiffness(1.0E+6 N/mm)
Iteration 2	Swift
Iteration 3	Huth-Schwarmann
Iteration 4	Grumman
Iteration 5	Tate & Rosenfeld
Iteration 6	Low Shear Stiffness (1.0E+3 N/mm)

Fastener loads are plotted for all 6 iterations. The percentage of load distribution on three series of fastener has helped to identify the appropriate empirical stiffness equation which closely matches with real scenario for our case.

Detailed Study

Bolted Lap joint metallic plate is illustrated below (Fig. 2)

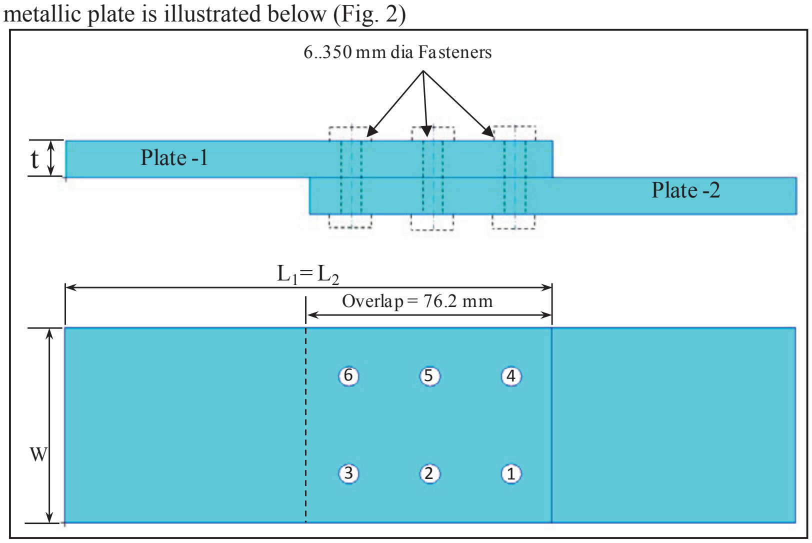

Figure 2. Bolted Lap Joint

FEM Details

Plates are assumed to be of aluminum alloy [8], and fasteners are Hi-Lok 12 (Ti Alloy). Plates are meshed with Two Dimension 4 Node Quad elements, Fasteners are modelled as CBUSH element with appropriate stiffness for each iteration (Equation 1, 2, 3 & 4). Two plates are pulled apart as illustrated (Fig. 3).

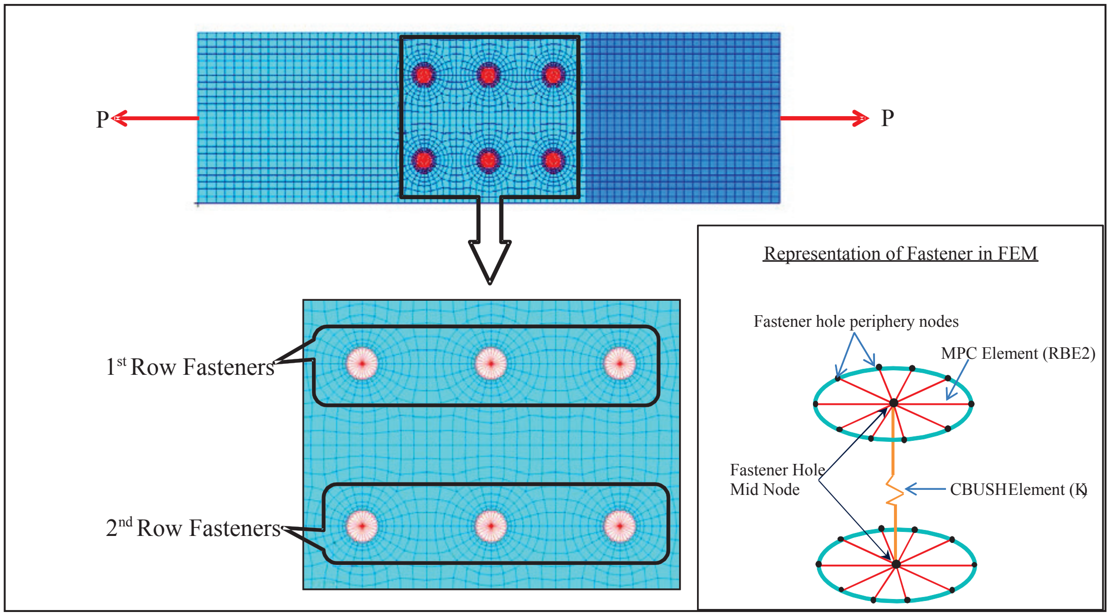

Figure 3. Bolted Lap Joint- FEM Representation

TABLE 2. Nomenclatures

Variable	Description
d	Fastener diameter (mm)
E_1	Young's Modulus of plate 1 (MPa)
E_2	Young's Modulus of plate 2 (MPa)
E_f	Young's Modulus of fastener (MPa)
t_1	Thickness of plate 1 (mm)
t_2	Thickness of plate 2 (mm)
f	Fastener Flexibility
K	Fastener Stiffness (N/mm)
n	Constant (1 for single shear, 2 for double shear)
a	Constant (2/3 for bolt, 2/5 for rivet)
b	Constant (3 for metallic bolt, 4.2 for composite bolt and 2.2 for rivet)

Shear Stiffness calculation based on Swift equation – Iteration 2

$$f = \frac{5}{dE_f} + 0.8\left(\frac{1}{t_1E_1} + \frac{1}{t_2E_2}\right)$$
$$K_{(swift)} = \frac{1}{f} = 109784\ N/mm \tag{1}$$

Shear Stiffness calculation based on Huth-Schwarmann equation – Iteration 3

$$f = \left(\frac{t_1 + t_2}{2d}\right)^a \frac{b}{n}\left(\frac{1}{t_1E_1} + \frac{1}{nt_2E_2} + \frac{1}{2t_1E_f} + \frac{1}{2nt_2E_f}\right)$$
$$K_{(Huth-Schwarmann)} = \frac{1}{f} = 69164\ N/mm \tag{2}$$

Shear Stiffness calculation based on Grumman equation – Iteration 4

$$f = \frac{(t_1 + t_2)^2}{E_f d^3} + 3.7\left(\frac{1}{t_1E_1} + \frac{1}{t_2E_2}\right)$$
$$K_{(Grummann)} = \frac{1}{f} = 36209\,N/mm \tag{3}$$

Shear Stiffness calculation based on Tate & Rosenfeld equation – Iteration 5

$$f = \frac{1}{E_f t_1} + \frac{1}{E_f t_2} + \frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} + \frac{32`}{`9E_f \pi d^2}\left(1 + \vartheta_f\right) + \left(t_1 + t_2\right) + \frac{8}{5E_f \pi d^4}\left(t_1^3 + 5t_1^2 t_2 + 5t_1 t_2^2 + t_2^3\right)$$
$$K_{(Grummann)} = \frac{1}{f} = 15987\,N/mm \tag{4}$$

FEM Assessment Summary

Fastener shear load plot for iteration-1 to Iteration 6 are as illustrated (Fig. 4).

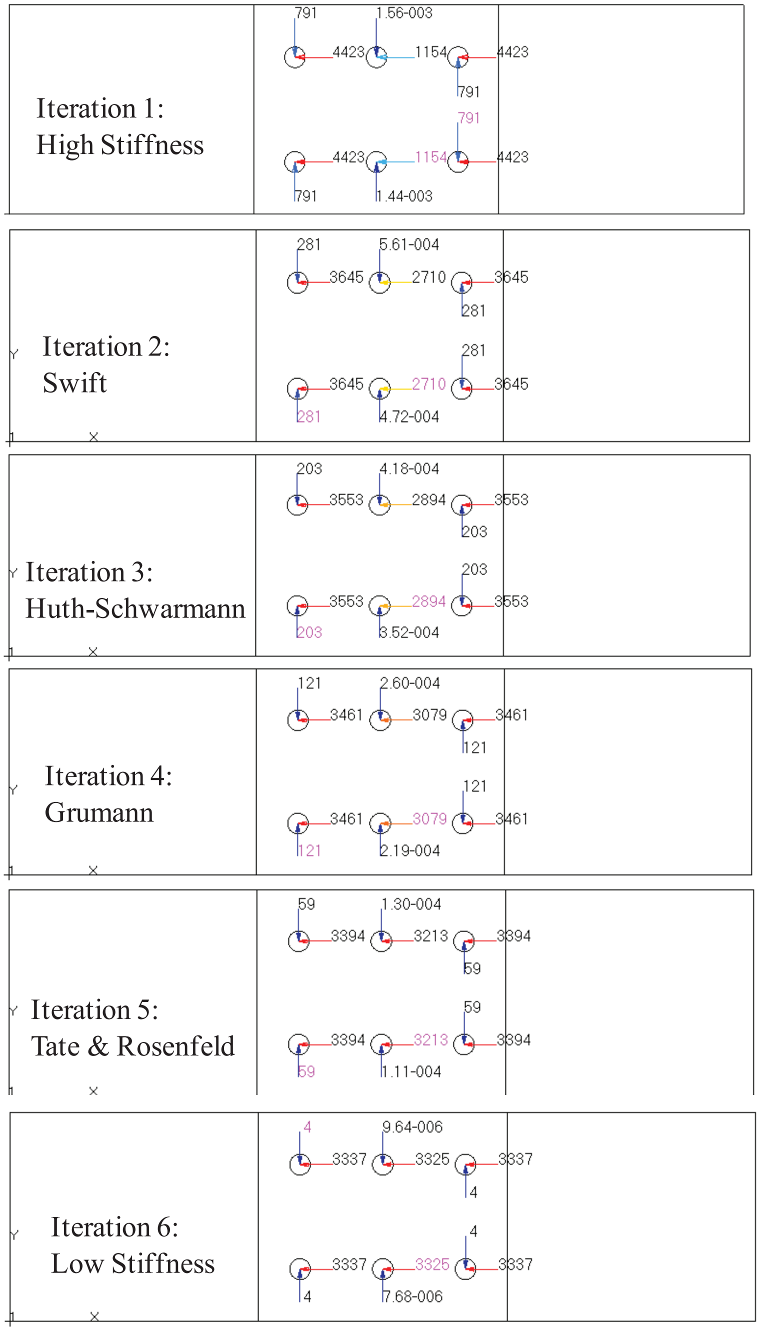

Figure 4. Fastener Shear Load plot

Graphical representation of Fastener Shear loads for Iteration 1 to Iteration 6 is illustrated (Fig. 5).

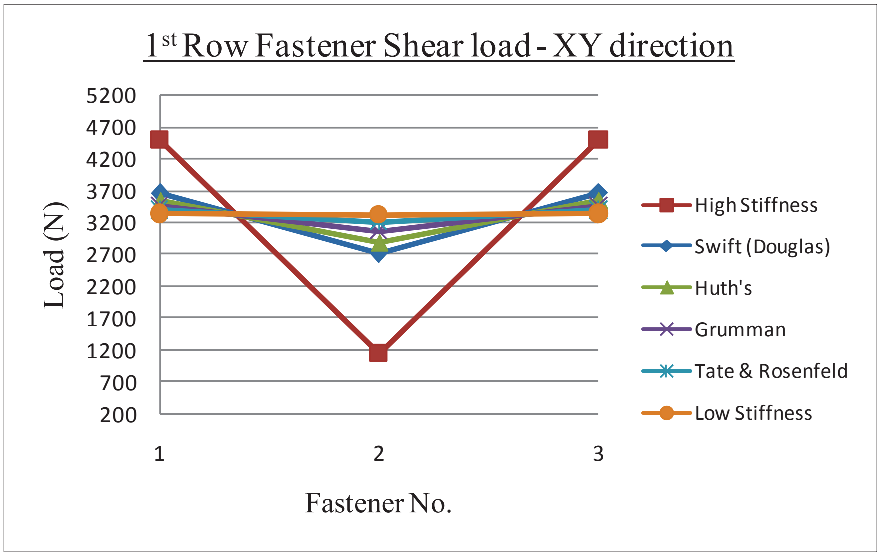

Figure 5. Shear Load distribution in a row of Fastener

Percentage of Shear load distribution in a row of Fastener for Iteration 1 to Iteration 6 is illustrated (Fig.6).

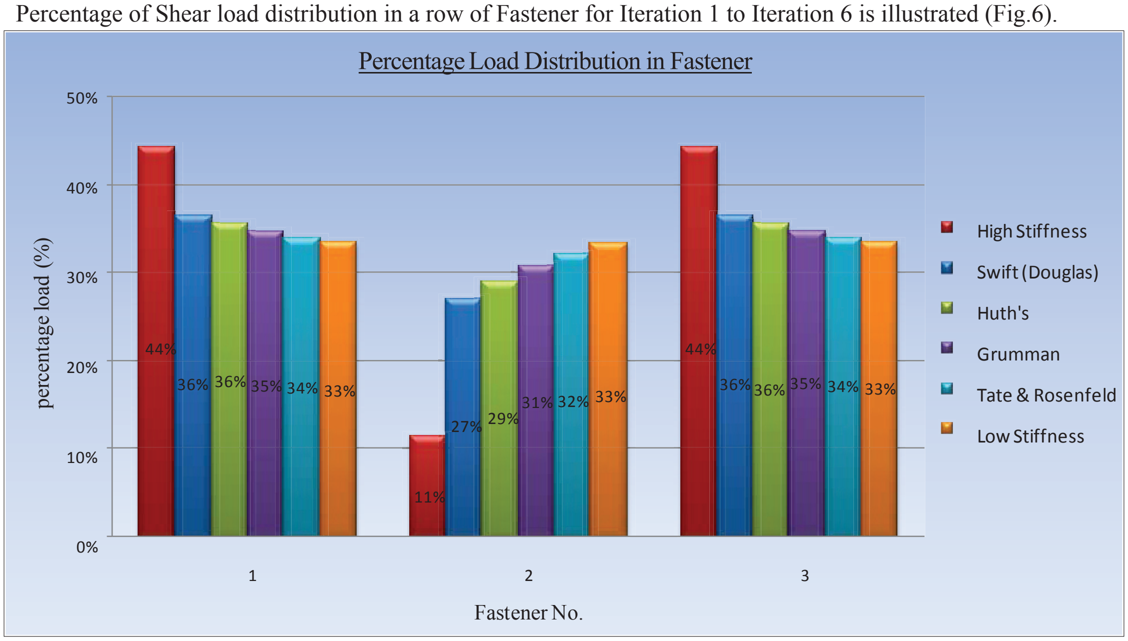

Figure 6. Percentage Shear Load distribution in a row of Fastener

Results and Discussion

From the simulation result plots (Fig. 4, 5 & 6) following is summarized.

- High Stiffness Fasteners- Iteration 1, would result in high loads at extreme fasteners and low load at mid fastener, Load distribution at Fastener 1, 2 & 3 are 44%, 11% & 44% respectively
- Low Stiffness Fasteners- Iteration 6 would result in infinitely flexible fasteners with exactly same load distribution across all the 3 fasteners. Load distribution at Fastener 1, 2 & 3 are 33%, 33% & 33% respectively

- Swift equation- Iteration 2 adds little flexibility to fasteners. However the loads at extreme fasteners are comparatively high when compared to mid fastener. Load distribution at Fastener 1, 2 & 3 are 36%, 27% & 36% respectively
- Tate & Rosenfeld equation- Iteration 5 adds further more flexibility to fastener resulting in almost uniform load distribution across all the 3 fasteners. Load distribution at Fastener 1, 2 & 3 are 34%, 32% & 34% respectively
- Huth-Schwarmann and Grumman equation- Iteration 3 & 4 adds realistic flexibility to fasteners. Load distribution at 3 fasteners is almost as per test data which is closely matching with 35%, 30% and 35% distribution.

CONCLUSIONS

From the above assessment it is observed that fastener load distribution obtained based on Huth-Schwarmann and Grumman equation for Aluminum Fittings closely matching with test date [1]. Hence either Huth-Schwarmann or Grumman equation can be used to calculate the reasonable fastener stiffness for Aircraft Fittings.

Huth-Schwarmann formulation can be preferred for aircraft structures, as Huth-Schwarmann equation also accounts for further Single or double shear joints and bolted metallic, riveted, bolted graphite/epoxy type of joints which are more popular in Aircraft structures.

With actual C-Bush stiffness fastener loads gets redistributed compared to high stiffened fastener model and it seems to be reasonable and acceptable.

We conclude from this study that fastener stiffness needs to be calculated using Huth-Schwarmann equation and this stiffness should be used in FEM's (CBUSH Stiffness). As aircraft industry is now steering towards weight reduction programs and stressing the engineers to design the components for optimal margins, hence this novel methodology in simulating fasteners yields accurate results leading to lean aircraft structures.

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