Fatigue Analysis of Riveted or Bolted Connections using the Finite Element Method

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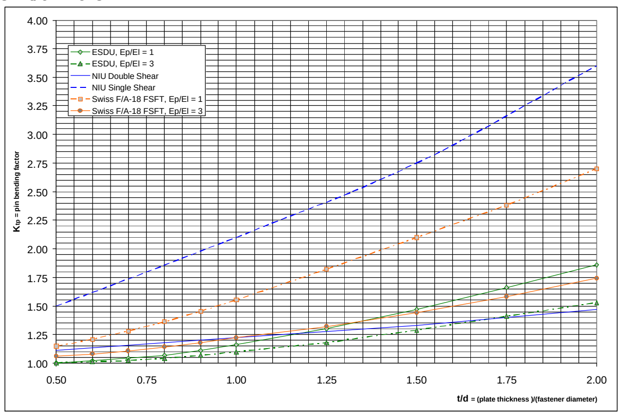
1. Abstract

The determination of the crack initiation life of a riveted or bolted connection requires a precise computation of the stress distribution around the critical fastener holes. For simple joint configurations, such as tension lap joints and lugs, and under certain conditions, the analysis can be performed by hand with an acceptable accuracy. For more complex joints this task can be very time consuming and the simplifications introduced in the hand calculation methods can lead to inaccurate results. Moreover, a comparison between several sources found in the literature has shown that big differences (up to 200%) can be obtained in the maximum stress prediction due to the pin bending effect when t/d > 0.5. The consequence is that, depending on the source used, extremely different results in the fatigue strength assessment of a connection are obtained. This unsatisfactory situation as well as the need for a more universal analysis technique, which can be used on a wide range of joints geometry, motivated the development of an analysis method based on the Finite Element Method.

2. Hand Calculation Methods

The hand calculation methods are based on curves presenting the stress concentration factors, which are to be applied to the bearing stress or the net stress, in function of the joint/plate geometry for standard loading cases. Most of the stress concentration curves found in the literature are similar with the exception of the pin bending factor (see Figure below), which show very large discrepancies (up to 200%) when t/d > 0.5.



Advantages

1. Accurate for simple cases such as tension lap joints and lugs
2. Quick for the cases mentioned above

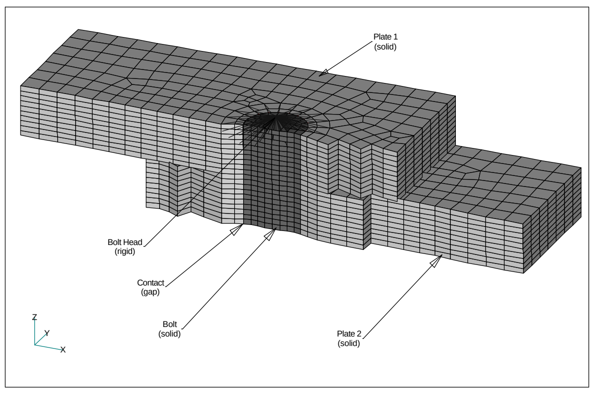
Disadvantages

1. Difficult and time consuming for more complex joints
2. Cannot account for secondary effects (local bending, etc.)
3. Not accurate for t/d > 0.5

3. Detailed FEM ("FE Method 1")

A very detailed way to model a bolted/riveted connection is to use solid elements to idealize the plates and fasteners, and to use gap/contact elements to account for the interaction between the fasteners and the connected plates. In practice, when connections including several bolts/rivets have to be analysed, this way of modelling can lead to severe convergence problems (MSC/NASTRAN solver). Moreover, high computational time is necessary to find a solution because the use of gap element requires many small load steps during the iteration process (factor 2 to 10 times more computational time regarding to the Simplified FEM described below). Therefore, this way of modelling is definitely not adapted to development projects, which require short design loops and quick responses to the problems.

However, the author believes that this is one of the most exact method, which can be used today to model this type of joints. Therefore, the Detailed FEM has been used as reference for the validation of the Simplified FE method described below.



Advantages

1. Very accurate
2. Can idealise complex joint configurations (3D)
3. Account for secondary effects (local bending, etc.)

Disadvantages

1. Time consuming meshing
2. Severe convergence problems when multiple fasteners
3. High computational time versus Simplified FE Method (factor 2 to 10)

4. Simplified FEM ("FE Method 2")

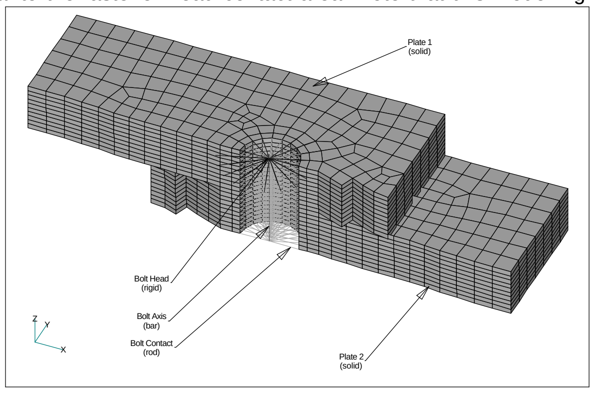
As for the Detailed FEM, the plates are idealized using solid elements. The bolts/rivets are idealized by bar elements to simulate the fastener axial and bending behavior and by rod elements to simulate the load transfer between the bolts and the connected plates. The bar elements are positioned along the fastener axis and have the E-modulus of the fastener material and the axial and bending properties of the fastener. The fastener axis is connected to the plate by means of radial rod elements, which lie in equidistant planes perpendicular to the bolt axis. The area of the rod elements (A_{rod}) is defined in such a way so that $A_{rod}=\pi dt/N_{rod}$ with N_{rod} being the number of rod elements used, d the fastener diameter and t the plate thickness. The rod elements have non-linear properties to account for the contact between the fastener and the plate, i.e. zero stiffness in tension and the E-modulus of the fastener material in compression. A rigid element (RBE2) on the bolt head side is used to simulate the bolt head, i.e. to ensure the axial load and the local bending moment transfer between the fastener and the plate. The plate surface area used to react these axial and bending loads is equal to the fastener head contact area. Note that this modelling method is able to simulate 3D bolting configurations.

Advantages

1. Very accurate
2. Can idealise complex joint configurations (3D)
3. Account for secondary effects
4. No convergence problems
5. Less iteration steps than Detailed FEM => 2 to 10 time quicker

Disadvantages

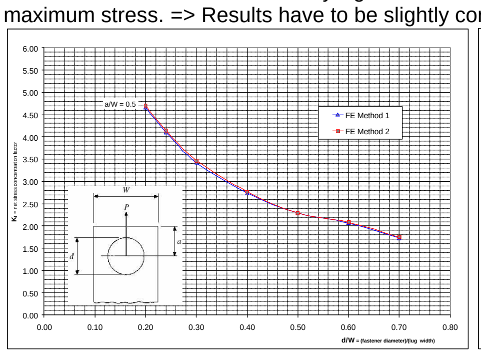
1. Time consuming meshing
2. Idealise a light interference fit => results have to be slightly corrected for clearance fit or interference fit fasteners

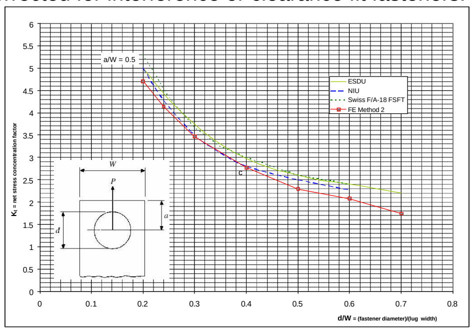


Results

Lug Net Stress Concentration Factor K_t

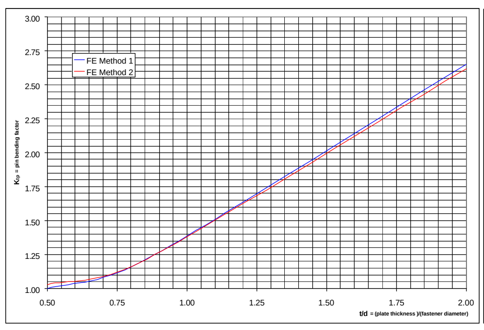
The left-hand Figure shows the comparison of the computed net stress concentration between the Detailed and Simplified FEM. A very good agreement is demonstrated with differences lower than 3%.The right-hand Figure shows a comparison between the curves presented in references [1], [2] & [3] and the Simplified FEM. A good agreement is shown and the differences lie between 0% and 20%, depending on which reference is taken as the basis for the comparison. The Simplified FEM leads to lower K_t than the ESDU [1] method throughout the entire d/W range. A possible explanation is that the FEM simulates a very light interference fit, which leads to a 10% shift down of the maximum stress. => Results have to be slightly corrected for interference or clearance fit fasteners.

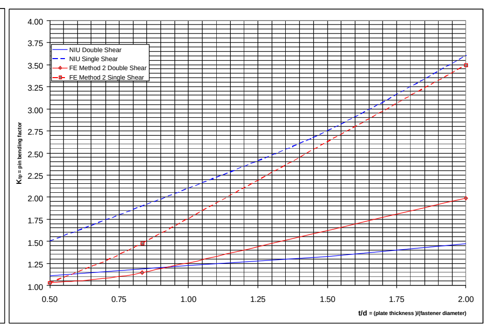




Pin Bending Factor K_{tp}

The left-hand Figure shows a comparison of the pin bending factor between the Detailed and Simplified FEM. Again the two modelling methods correspond fairly well with each other. The right-hand Figure shows a comparison between the curves presented in [2] and the Simplified FEM curves for single lap joints and double lap joints. Both methods show the same trend in the K_{tp}, but substantial differences are observed. Reference [2] mentions that the given curves are presented as a guide for preliminary design. Moreover, detailed studies revealed that the stiffness of the connected parts as well as the stiffness of the surrounding structure or the boundary conditions play a major role in the K_{tp} value for t/d > 0.5. => The use of FEM is strongly recommended for t/d > 0.5.



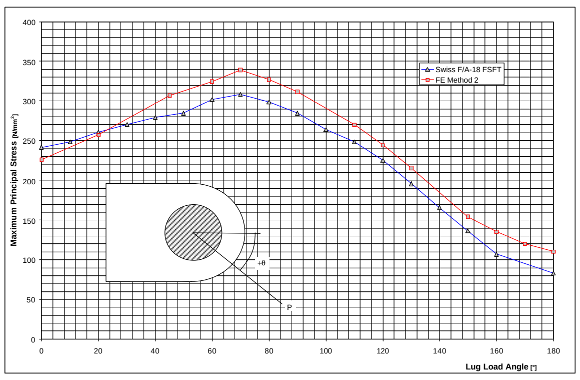


Load Angle Influence

The maximum principal stress around a fastener hole is dependent on the loading direction. In other words, the maximum stress depends on the way the fastener load is reacted in the plate: tension, compression or shear. A study have been performed on a round-ended lug with the loading angle varying from 0° to 180°. The lug geometry was defined as the following: a = 55mm, d = 54mm, W = 110mm and t = 22.5mm. The lug and the pin are made of aluminium.

The Figure on the right presents the computed maximum principal stress for the lug geometry described above in function of the load angle using ref. [3] curves and the Simplified FEM.

A very good agreement has been found with a difference remaining below 10% for loading angles up to 150°. For loading angles between 150° and 180° the correlation is less good and the difference can reach 25%. However, at these high loading angles the maximum stress is lower by a factor 2 to 3 than at smaller loading angles.

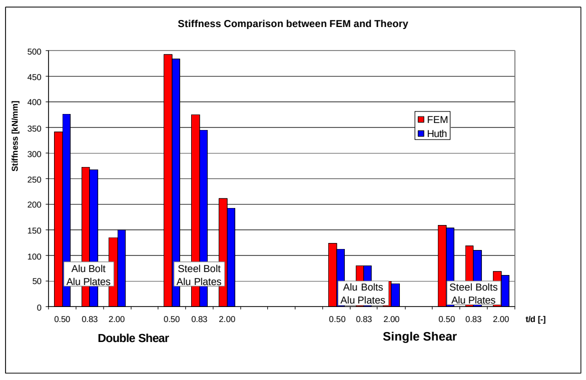


Fastener Stiffness

In multiple fasteners joints an accurate assessment of the fastener flexibility is paramount for the determination of the load distribution within the joint. Several semi-empirical formulas for the calculation of fastener flexibility exist in literature. According to [4], these formulas turn out to be inaccurate or at least not applicable for a wide range of joint geometries. An extensive experimental investigation have been performed [4] during which fastener flexibilities for a wide range of joints of practical interest were determined.

A formula for fastener flexibility has been derived [4] from the tests results and proved to be significantly superior to those found in literature.

A comparison of the joint stiffness computed with [4] and the Simplified FEM for different bolted joint configurations is presented in the Figure on the right. The correlation is very good with differences staying below 10%, thus showing that this modelling method can accurately predict the joint stiffness.



[1] ESDU, Data Item 81006: Stress concentration factors of axially loaded lugs with clearance-fit pins.
[2] Airframe Structural Design, Michael C. Y. Niu
[3] Swiss F/A-18 FSFT
[4] Fatigue in Mechanically Fastened Composite and Metallic Joints, ASTM STP 927
Influence of Fastener Flexibility on the Prediction of Load Transfer and Fatigue Life for Multiple-Row Joints, Huth

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