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Novel Methodology for Assessment of Bolted Joints Under Vibration Fatigue

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Abstract

Smart industrial revolution in any organization brings faster product delivery to market which can meet customer expectation and full life requirement without failure. Failure per machine (FPM) is very critical metrics for any organization considering warranty cost and customer perception. One such area which needs a detailed evaluation is bolted joint. Bolts play a pivotal role when integrating a subassembly with the main structure. Often, it is challenging to address bolt failure issues due to vibration induced in structures.

Current bolt virtual evaluation methods help to evaluate bolts in simple loading conditions such as axial and bending loads. But it is quite complicated to evaluate the bolts which are prone to vibration loading as traditional method of using the gravity loads misses out on dynamic characteristics hence it must be simulated using modal dynamic analysis but, with current vADV (virtual accelerated design verification) method it is not possible to capture correct physics as modal analysis converts all frictional contacts to bonded contact resulting change in load path.

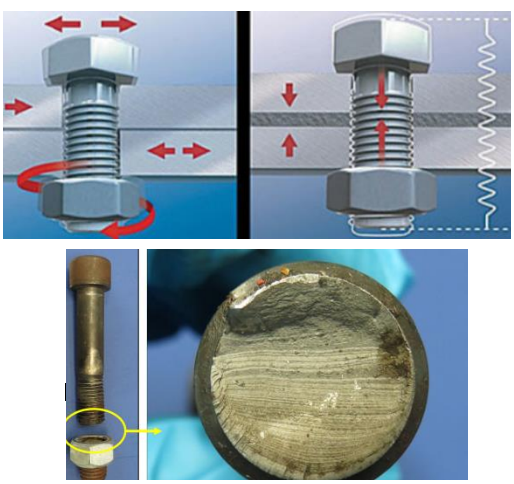


Image 1: Bolted joint load path and bolt failure [1]

different methodologies to evaluate bolts under vibration fatigue.

- Contact optimization of a bolted joint using contact pressure and load path study
- Acceleration extraction using modal dynamic analysis and load super-position.

Both the methods have shown good correlation with field data and have been utilized in ongoing product development programs to address ADV failures. Pros and cons of these methods are understood and documented in this study.

Keywords: Bolted joint, Vibration Fatigue, vADV, Field failure co-relation

Introduction

Off highway vehicles are prone to ground engaging and transport loads which induces enough oscillations which can cause slender structures to vibrate at higher amplitudes. Such examples could be railing or bracket structures of a construction or forestry machines. Usually, these substructures are integrated with the main machine structure with the help of bolted joints as bolts are one of the most standardized and preferred machine elements for connection and load transfer. These bolted structures when subjected to excess vibrations and proportionate acceleration levels; become susceptible to failure.

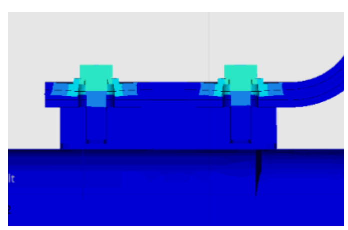


Image 2: Bolted joint load path and strain distribution

Since the mechanics of highly stressed bolted joints and the thread fatigue are complex issues, the design and validation of such joints is frequently carried out with major simplifications and assumptions, leading to either over-engineered solutions or to premature failures of the prototypes. Evaluating bolted joint for fatigue itself is a complex phenomenon and with vibration loading it further adds challenges in terms of modeling and simulation. In this study to address the earlier mentioned challenges, one failure incidence on Deere excavator machine is considered and the proposed methodologies of bolted joint evaluation under vibration fatigue are validated.

Methodology

Problem statement:

The existing methodologies for evaluating the bolted joints are:

1. Inertia/gravity load analysis
2. Vibration fatigue

Both these methodologies have their own challenges. The inertia load analysis misses out on capturing the dynamic behavior and stiffness direction change which leads to incorrect design as this is a conservative approach. Whereas, during vibration fatigue analysis the eigen value extraction solver converts all frictional contacts to bonded contacts which changes the actual load transfer path.

To address, these challenges and for better FEA correlation with the test data, two new approaches are proposed:

1. Load Super-position + Modal Super-position:

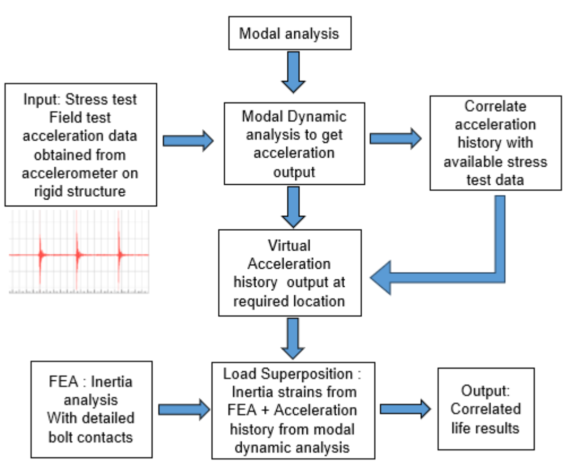


Image 3: Flowchart - Load Super-position + modal Super-position

The first step in this methodology is to perform the modal analysis on the structure under consideration which is subjected to vibration fatigue. The FE model is Constrained at drive point (where rigid body motions are extracted from test) and run for modal analysis. The output from FEA modal analysis and the displacement time history data derived from stress test accelerometer on the rigid structure is utilized to perform modal dynamic analysis which yields mode scaling factors to get acceleration output at desired location. The stress history is created from modal participation factors and modal stresses as per equation 1[2].

$$\sigma_{ij}(t) = \sum_{k} P_k(t) * \sigma_{ij,k} \tag{1}$$

Where,

σij(t)	Stress history for the given time interval of an element
Pk(t)	Participation factor per mode at time *t* (via mrf/pch file)
σij,k	Modal stress of an element per mode (via h3d file)
k	Mode

The virtual acceleration derived through this process is now superimposed with the strains obtained from inertia analysis performed with detailed bolt modelling. This is the load superposition step which further allows to extract life results on the requested components. The life results obtained through this process are correlated with the life of failure component. The correlation is found to be decent only within the bolted joint area.

This method is more useful while evaluating comparatively rigid structure which doesn't have dynamic behavior within assembly/subsystem. Although this process is quite useful for hot spot prediction there is scope to improve correlation and get correct values for absolute fatigue life.

2. Contact optimization + Modal Superposition

This process is a further refinement of method 1 to achieve better correlation with stress test results. Contact optimization is the key differentiating factor in this methodology.

The major challenge in the regular bolt modelling during modal analysis is that the solver converts all the contacts to tie pair or bonded contact. This does not define the actual load transfer path of the bolted joint as the load is also transferred through the components which are bolted together. But the practical condition would be such that majority of the load should pass through the bolts. If we are able to recreate this scenario in FEA then only we will be able to get actual stress/strains to which the bolts are subjected.

Image 4 explains the approach followed during the bolt modelling to optimize the contact behavior. The contacts are optimized are in such a way that bolts experience majority of the load transfer giving close to actual life results as seen in the stress test.

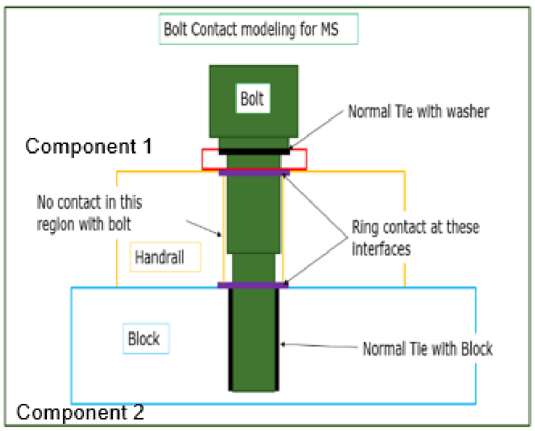


Image 4: Bolted joint interface contact modelling

The bolt is given tie contact with the washer on the head side. The thread part of the bolt is also tied with component 2. No contact is given in the shank region of the bolt. A ring contact is given between the washer (red) and component 1 interface. Between component 1 and component 2 again a ring contact with limited patch in contact is provided instead of giving contact over the entire area which is shared by component 1 and component 2.

This method ensured that when the contact is converted into tie pair, very limited load is transferred through this path which in turns allows maximum load to pass through the bolt. The steps to be followed in this methodology are shown in image 5.

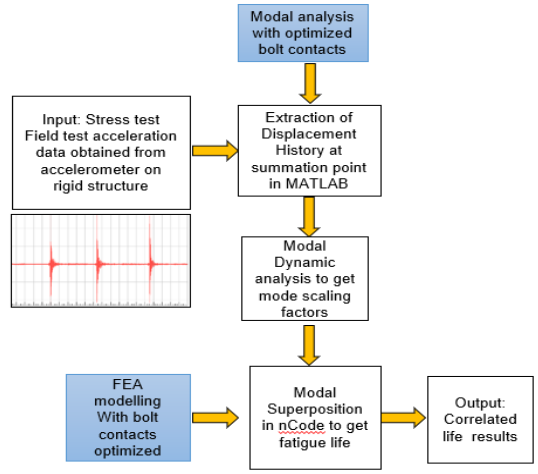


Image 5: Flowchart – Contact optimization + modal Super-position

Results and Discussion:

From the above study it is quite evident that the analysis of bolted joints subjected to vibration fatigue is having significant impact of load transfer path modelling. It is challenging to match the outcomes of test data for such components with either normal modal analysis or fatigue analysis such as inertia load cases. Instead, a combination of modal and inertia analysis with help of superposition techniques along with the acceleration data from stress tests can yield realistic results.

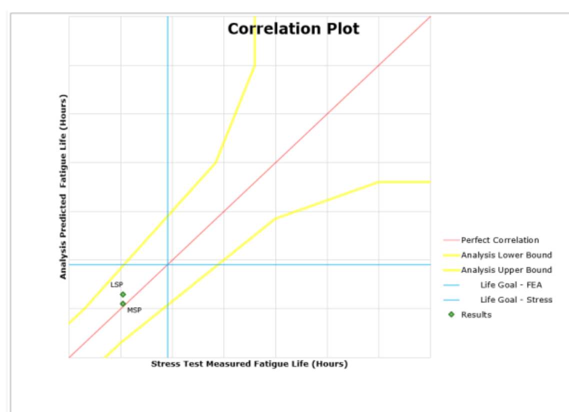
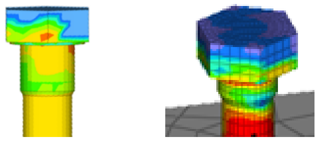


Image 6: Correlation plot of method 1 and method 2

The life correlation from FEA and that from stress test was 57% for method 1 and 89% by method 2 in which contact optimization is done along with modal superposition. The correlation plot is shown in image 6. LSP stands for method 1 with load superposition and MSP stands for method 2 with modal superposition and contact optimization. The contours of bolt life are shown in image 7.



(a) (b)

Image 7: (a) Method 1 - Bolt life contour
(b) Method 2 - Bolt life contour

Summary/Conclusion:

Each methodology has its own challenges such as accuracy of results, availability of appropriate data from stress tests, multiple data conversions, higher analysis time etc. Despite these challenges the methodologies discussed in this paper achieved better correlation of life results on bolted joints subjected to vibration fatigue compared to conventional way of analysis. The other key highlights/impacts of these approaches are:

- Able to simulate the actual modal behavior experienced on the machine.
- Optimized and efficient design solution for small space
- Reduced risk of failure in durability with Reduced Up-time.

The further scope of study in this area would be mathematical verification for the contact area of bolted joint members based on contact pressure and contact optimization quantification study.

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