Fatigue Life Prediction of Welds in Motorcycle Frames on a Rough Road

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Abstract: *Motorcycle production is increasing with strong demand for commuter models. These models are used for commuting and transporting goods with total demand in excess of 40 million units per year mostly in Asia. For production efficiency and lower cost, frames are made by welding steel pipes together forming different welded joints. The welded joints are used to make the frame compact and to provide necessary stiffness. With most welded parts, the most prone to fatigue failure is at or near the weld. Although reinforcing or strengthening can be done, cracks will just grow on different parts of the weld or joint. Thus, the need for simulation is very important to investigate the problem and consider proper design early in the development stage. This paper compares the Hot Spot Stress method and Equivalent Structural Stress Method (Verity method) to predict fatigue life of the welded joint. Rough road signals were used to evaluate the durability of the frames. The location and life were validated with test results. fe-safe and Verity showed great promise in predicting fatigue of welds but a lot of manual labor is needed. Parameters like plate thickness, reference nodes, weld line nodes, start element and start nodes, etc, are still needed. To shorten the design time, Yamaha Motor developed a method in-house to create the input parameters automatically. Thus shortening the time required to prepare the analysis files as well as the ability to analyze between 100-200 welds which will be otherwise nearly impossible if done manually.*

Keywords: *Motorcycle frame, Fatigue life, Weld, Welded joints, Structural Stress.*

1. Introduction

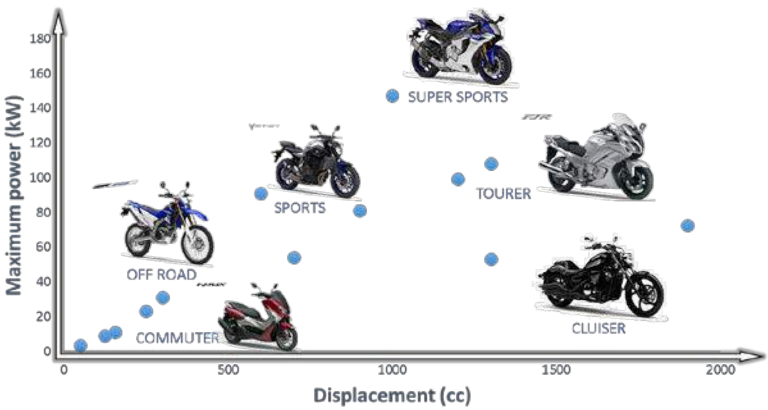


Figure 1. Types of Motorcycles.

Motorcycles are categorized depending on usage and application. Figure 1 shows the categories of these two wheeled vehicles namely, Sports (some are categorized as super sports), Tourers, Off roaders, Cruisers and Commuters. Yamaha Motors released its first motorcycle YA-1 in 1955 (see Figure 2) with its frame composed of welded pipes.

Figure 2. Yamaha Motor's first motorcycle YA-1 (year 1955).

The frame system of a motorcycle supports the load (i.e. Passengers and goods) and is also exposed to the effects of the road. Frames always appear to suffer fatigue damage. Fatigue life of the frame will ultimately decide the service life of a motorcycle.

The more expensive types of motorcycles have higher requirements for power output and performance. The frames of Tourer and Super Sports are usually made of aluminum and are casted in one piece. These frames are lightweight and highly rigid or stiff. Due to the economic development and population growth of many countries in Asia especially South East Asia and India, it lead to increasing demand for motorcycles. The two-wheeled vehicles are cheaper, easier to operate and consume less gas compared to cars. There is a big need to cater to countries with growing population but have lower per capita income. Thus motorcycles being sold there have to be cheaper and should still be able to withstand loads from people and goods being transported. These loads are also be magnified by the type of roads. These types of motorcycles are categorized as Commuter motorcycles.

Total demand for Commuter types have exceeded 40 million units per year (Yamaha, 2016) and is still increasing. There are many requirements for Commuter motorcycles. Aside from the lower price tag, frames have to be rigid at the same time easy to produce. Frames need also be compact, easy to manufacture and can be redesigned for different needs and for different regions. Steel pipes satisfy a lot of the requirements. Pipes are mostly welded together by arc welding to form the frames see Figure 3. The frame is a collection of pipes and plates. Two pipes and one plate are connected with seam welds. Welding makes manufacturing faster and easier. Prototypes can also be created at a lower cost and at shorter time in comparison to those requiring molds for casting. However, due to the welding process, the weld introduces a lot of considerations. The welding process produces stress singularities, high residual stresses and Heat Affected Zone (HAZ). Stress singularities make the stresses at the weld toe higher or produce stress concentrations. Residual stresses will have adverse effect on the parts while HAZ will weaken the material by cancelling the effects of tempering and/or quenching.

Figure 3. Pipes and plates welded together to form the frame.

Therefore, fatigue cracks are likely to occur in these areas specially the weld toe (part of the Heat Affected Zone). This makes development very difficult. Countermeasures by reinforcing with more seam welds will just change the location of the crack site. Therefore, there is a need for simulation to investigate the problem and to consider a more effective solution during the design phase. Figure 4 shows fatigue cracks occurring at the weld toe.

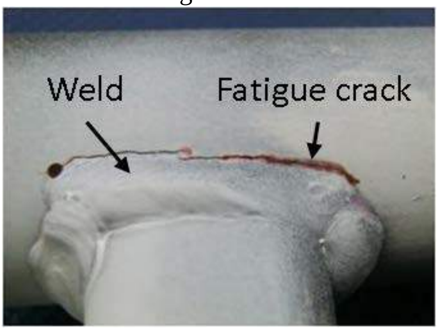


Figure 4. Fatigue cracks at the weld toe.

2. Literature Review

This study also presents a review focused on fatigue analysis of motorcycles. A few articles are summarized and important points were discussed.

(Zhang, 2014) studied the failure of a motorcycle frame system based on road test and finite element method. They created a finite element model and multi-body dynamic model of the frame to obtain results of stresses based on the road tests. The main task is to discover the weak parts of the frame and obtain fatigue life. Two different materials are used namely carbon steel Q235 and cast magnesium alloy AZ91. The stresses were comparable for both materials but Cast Magnesium alloy has a much lower weight. However, the fatigue life of the lighter frame was lower due to weaker fatigue properties of the material.

(Gobbi, 2014) analyzed an off-road motorcycle frame and modified it to optimize its fatigue life. Static tests bench results were used to validate the finite element model and got errors with 5% of the test data. The mission profile is dominated by off-road use and stress levels are close to the yield point. The presence of connections in motorcycle frames which includes assembling different beams using seam welds, makes the analysis very complicated. The most probable failure zone is the weld as intimated by the authors and of course well known in the manufacturing world. Shell elements were used and also the shape of the frames were optimized to increase fatigue life of the critical areas. The fatigue method used for the weld follows the notch stress approach by (Radaj, 2009) on the fictitious radius and using sharp notches and also looked into multi-axial methods. To improve fatigue life, the frames were redesigned by changing material and improving the connections. With improvements, some crack zones have disappeared and the frame has a longer fatigue life. Predictions of fatigue life were between 1.09 to 2.35x of test life.

(Lin, 2005) did a study on fatigue analysis of motorcycle handlebars. They conducted experiments and compare it to fatigue analysis results. The Belgium road was used as the applied loading. Three methods were used to analyze the fatigue life. Traditional S-N approach, British Standard (BS 5400) and BS 5400 with Gurney thickness modification were compared. Only the “BS 5400 standard with Gurney thickness modification” gave satisfactory result and their acceptable range was 2.5 times compared to the experiments.

Finally, (Knott) gave us an insight on how to design motorcycle frames. He experimentally obtained the stresses and then computed them theoretically showing acceptable correlation. In addition handbooks were also used to validate his results. The stresses were very low compared to the fatigue limit of the material. Some insights in his research includes avoiding disproportionate members and avoiding the need for bends to connect or weld parts together. Also avoid filling gaps with welds by making sure to design having a “fish mouth” to properly conform the connect part to the round end of the tube. With better joints, fatigue failure will still be in the same location and pattern albeit with a longer life. Bending fatigue caused crack propagation and catastrophic failure at several locations near the weld. This is due to stress concentration factors and dynamic loading. Dynamic loads including inertial loads increase the loading beyond the peak static load.

A study on some of the research on fatigue of motorcycles were done. Yamaha Motors have a lot of experience in designing motorcycles internally. Experiments were also done on a consistent basis to validate design objects. Nominal stress method as proposed by standards was used but the method has a lot of subjectivity. Determination of nominal stresses, extrapolation method, joint type selection, stress concentration factors are a few of the subjective parameters that will change prediction accuracy. In addition, fatigue curves were prepared in house using experiments as well. With many parameters involved, it became too difficult to prepare simple fatigue curves corresponding to various joints, sizes and loading modes. Thus, it became necessary to rely on vehicle durability tests. The purpose of this study is to find a numerical method to minimize testing, to develop best design practice and of course to be able to apply proper simulation during the design phase.

3. Hot Spot Stress or nominal Stress Approach

Although stress concentration due to discontinuities in the welding is the main cause of fatigue cracking, it is not realistic to evaluate local stress concentration of the entire frame. Most fatigue design of welded structures are based on the nominal stress or hot spot stress approach (Dong, 2001) (JSSC) (BS 7608, 2014). These use a series of weld S-N curves and are well accepted in most industries and recommended by many international codes and standards. Two main bodies are the Japanese Society of Steel Construction (JSSC) and the British standard BS7608 updated in 2014 (BS 7608, 2014).

The JSSC produced a document titled "Fatigue Design Recommendations for Steel Structures" while the BS 7608 is called "Guide to Fatigue Design and Assessment of Steel Products". Both of these codes give methods and guidance for assessment of the fatigue life of steel parts subjected to repeated stress fluctuations. Base material as well as welded parts are included. BS7608 proposed a cycling counting method using reservoir method (BS 7608, 2014) (which gives very similar output to the Rainflow Counting Method). Figure 5 shows the S-N curves for different weld types from the updated BS7608 (BS 7608, 2014). The BS5400 was first developed for bridges and later on replaced by BS7608, which was created for all steel structures.

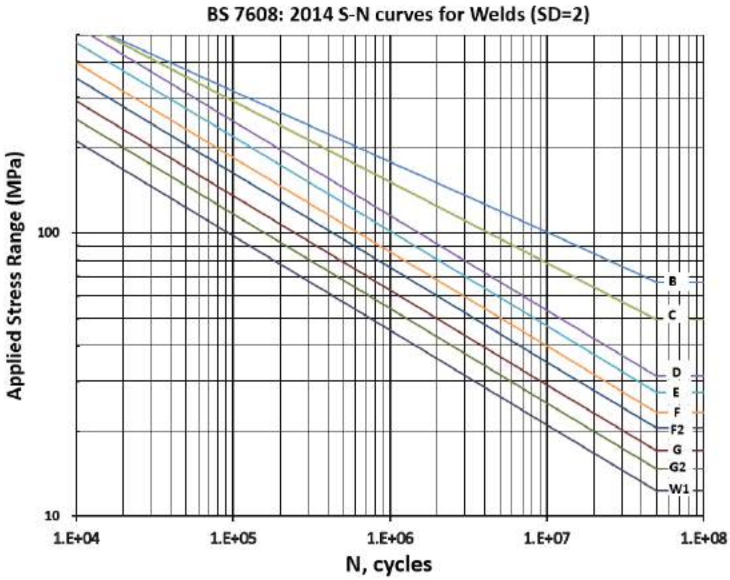


Figure 5. S-N curves for different weld types (BS7608:2014).

The Hot Spot Stress method is still commonly used to determine the fatigue life of the welds. It first takes into account the stress distribution by using extrapolation of the stresses near the weld zone and uses that stress as the nominal stress (JSSC). The method can either be used with stresses from experiments or from finite element analysis.

There are three main obstacles in using Hot Spot Stress method. First is that finite element stress values change with different element sizes and there will be a need to verify with experiments on which element size is good enough. Second, the extrapolation method will have an effect on the values of the extrapolated stress. Finally, most welds in a motorcycle frame cannot be simply classified into the main joint types from the standards.

4. Verity and the Structural Stress method

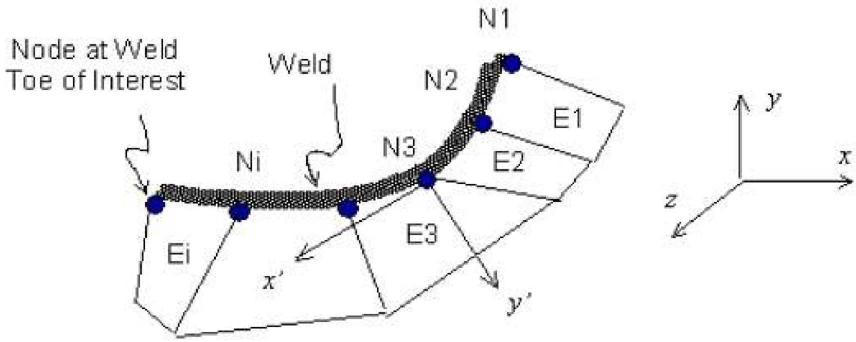


Figure 6. Arbitrary curved weld with nodal forces (Verity Manual, 2011).

As discussed in (Dong, 2001) and (Dong, 2007), Structural Stress can be used as a way to reduce the effect of sensitivity due to the stress concentration at the weld toe. Since the Structural Stress definition is consistent with structural mechanics and can be used as a measure of state of stress in the weld. It satisfies equilibrium and equivalent to the effect of local stress distribution. Imposing the equilibrium equations on the state of stress should reduce or eliminate the mesh-size sensitivity of the calculation. Similar to most fatigue analysis, conventional finite element results can be used directly as a post-processing procedure. The nodal forces are used to compute the Structural Stresses which are separated into membrane and bending forces or rather into forces and moments. Using a curved weld in Figure 6, the line forces can be computed in a way 2nd order quadratic element shape functions are used. The nodal forces thus can be related to line forces along the weld as follows (Verity Manual, 2011)

$$\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ \vdots \\ F_{n-1} \end{Bmatrix} = \begin{bmatrix} \frac{(l_1+l_{n-1})}{3} & \frac{l_1}{6} & 0 & \frac{l_{n-1}}{6} \\ \frac{l_1}{6} & \frac{(l_1+l_2)}{3} & \frac{l_2}{6} & 0 \\ 0 & \frac{l_2}{6} & \frac{(l_2+l_3)}{3} & \frac{l_3}{6} \\ 0 & 0 & \dots & \dots \\ \frac{l_{n-1}}{6} & 0 & \frac{l_{n-2}}{6} & \frac{(l_{n-2}+l_{n-1})}{3} \end{bmatrix} \begin{Bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_{n-1} \end{Bmatrix}, \qquad (1)$$

where F_i are the forces and f_i are the line forces along the curve, l_i represents the element edge length. The fractions are defined as such due to the shape functions. Similarly, line moments are calculated in a similar manner. Although not shown here, coordinate transformation of the nodal forces and nodal moments are needed to be performed. Finally the Structural Stresses at each node can be computed as

$$\sigma_s = \sigma_m + \sigma_b = \frac{f_{y'}}{t} + \frac{6m_{x'}}{t^2} \quad , \qquad (2)$$

where σ_m and σ_b are the membrane forces and the bending forces respectively, t is for thickness of the plate and f and m are the corresponding line moments and line forces. Equation 2 can be realized as simple beam equations.

Having the Structural Stresses, the master S-N curve approach was formulated based on Structural Stresses, stress intensity factor of the crack, loading mode and crack growth using Paris Law. Introducing the Equivalent Structural Stresses parameter as follows,

$$\Delta S_s = \frac{\Delta\sigma_s}{t^{*(2-m)/2m} \cdot I(r)^{1/m}} \quad , \qquad (3)$$

where t^* is the relative thickness (with respect to a unit thickness), ($m=3.6$), $I(r)$ is a dimensionless function of the bending ratio computed by integrating the two-stage crack growth (Verity Manual, 2011) (Dong, 2001). The equivalent stress has the stress unit. *I(r)* can be used for either load-controlled or displacement-controlled conditions. With these, (Dong, 2007) have shown the effectiveness of the procedure by using a collection of existing weld S-N data of various joint types and were reprocessed to produce Structural Stresses. Then using the results, using a single master S-N curve was shown to be feasible. Reducing the weld classification based S-N curves into a single S-N curves and thus reducing subjective decision making from the designer or analyst. Figure 7 shows the master S-N curve incorporating about 800 fatigue tests. All welds have residual stresses in place and these were used as an advantage. The fatigue tests have residual stresses which are not separately studied as a parameter. Thus, the master S-N curve indirectly includes the effect of the residual stresses. Verity, incorporating all of these, is owned by Battelle Institute and is licensed exclusively to Dassault Systemes Simulia and used within the fe-safe GUI.

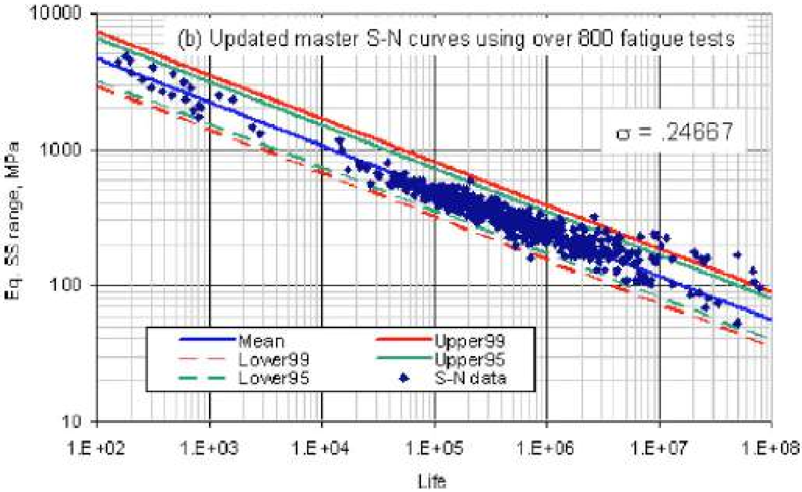


Figure 7. Structural based Master S-N curves incorporating 800 fatigue tests (Dong, 2007).

A lot of studies were able to show that the Structural Stress method is mesh insensitive. As part of our validation in Yamaha Motors, proper documentation on sensitivity of the Structural Stresses is created and checked. Figure 8 shows the comparison between two different element size meshes. It also shows the result for principal stresses as a comparison. As can be seen, even with different element sizes, Structural Stresses gives better results in comparison to the principal stresses.

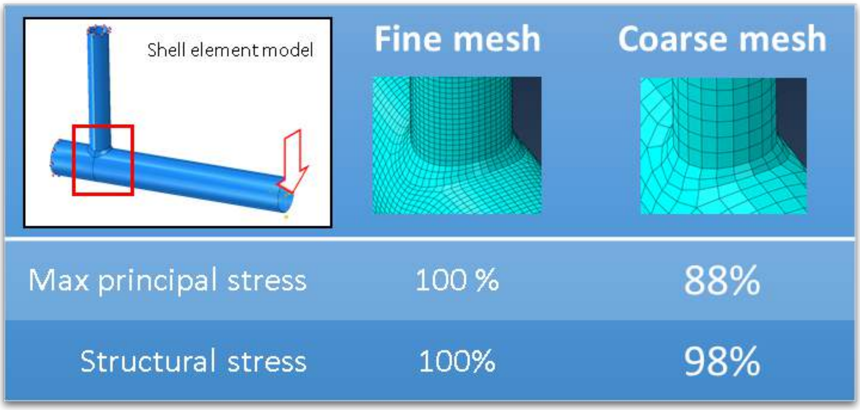


Figure 8. Comparison between Structural stresses versus Principal stresses with different mesh sizes.

5. Experimental Results

5.1 Motorcycle Handles

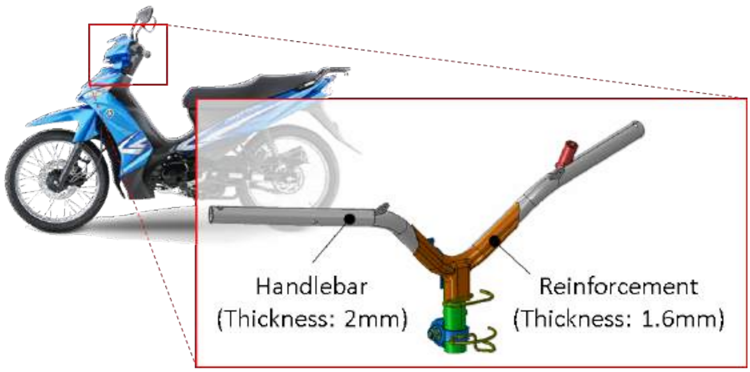


Figure 9. Illustration of motorcycle handle.

Different parts of the motorcycles were used to compare experiments and the aforementioned methods. The first joint type is the motorcycle handle. In Figure 9, pipes of 1.6mm to 2.0 mm thicknesses were connected to form a handle. Figure 10 shows a photo of the fatigue test setup. The direction of the loading is also added to give an idea of how loading is applied. Loading frequency is 10 Hz. Figure 11 plots the strain versus number of cycles and gives an idea on when the testing was stopped. Visual inspection was done and when the crack suffered a through thickness crack, the tests were stopped. In Figure 12, through thickness crack can be confirmed by the striations. The striations represent local crack growth in the cycles. As the crack advances towards the thickness of the plate, the striation diameter or crack area widens. The crack diameter grew to about 8mm, see Figure 12. The selection of this criteria follows the recommendation for Verity. Verity method uses Paris law to propagate the crack from the weld line through the thickness of the plate.

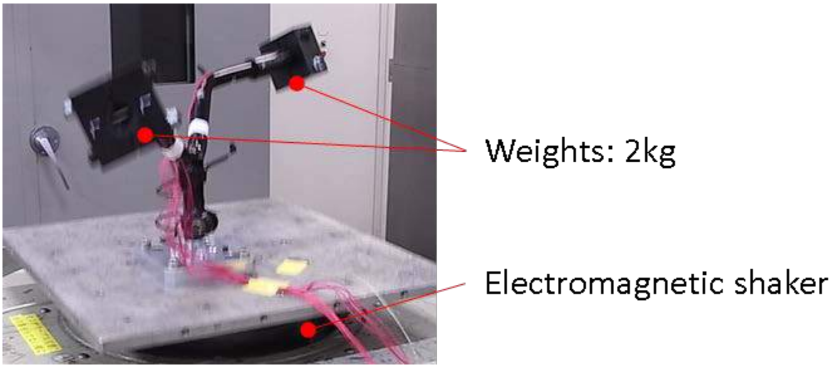


Figure 10. Actual test setup of motorcycle handle.

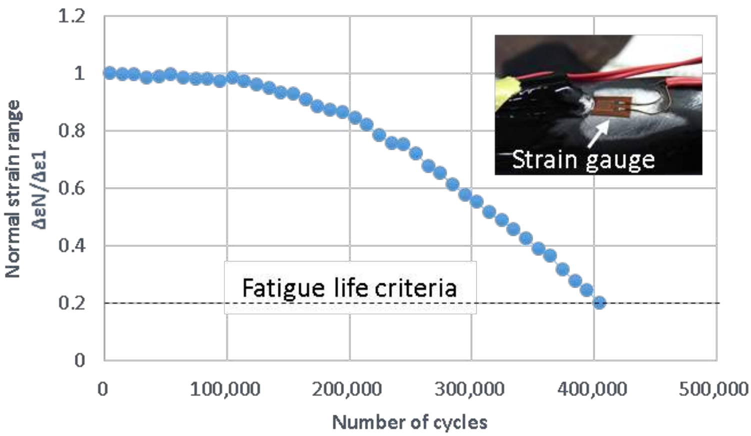


Figure 11. Strain vs number of cycles.

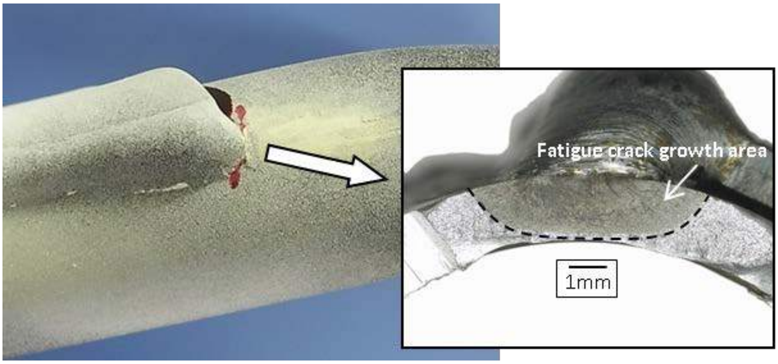


Figure 12. Photos of actual crack site and failure in the motorcycle handle.

The analysis was first done with a simple shell model including the weld bead modelled as shell elements in Figure 13. The life prediction was very different from the tested handle. The test gave a life of around 400,000 cycles while the first handle model gave a life of more than 1.3M cycles. The shell is modified to follow the actual contour of the weld in the handlebar. Figure 14 shows the recommended mesh model for curved welds .The modified model has a life prediction of 366,000 cycles which is around 9% difference from the actual test life. The modified model has a larger weld bead and thus able to transfer the forces properly to the toe. Figure 15 shows the difference between the two mesh model as well as the resulting Structural Stresses. As can be seen, the weld end if modeled properly will introduce higher Structural Stresses as expected.

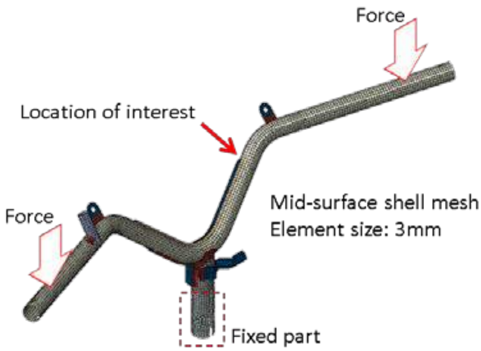


Figure 13. CAE mesh model, boundary conditions and loading in the motorcycle handle.

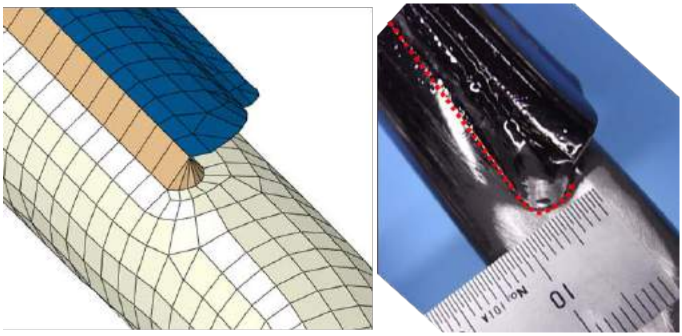


Figure 14. Modified model in comparison to the actual geometry.

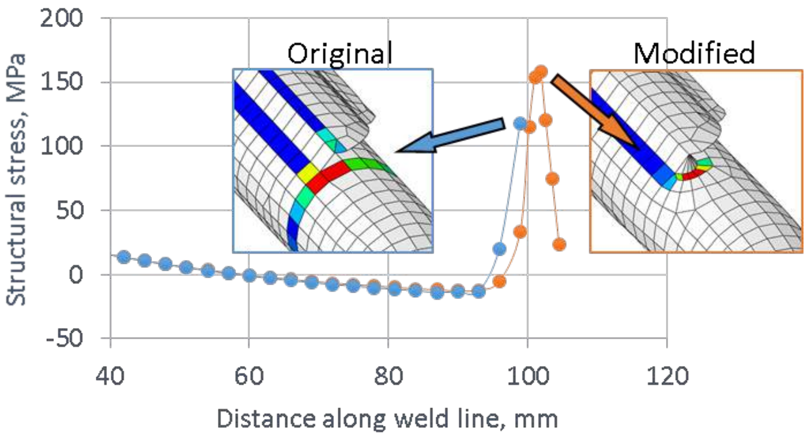


Figure 15. Comparison of the Structural Stresses between original and modified mesh model.

5.2 Other Frame parts

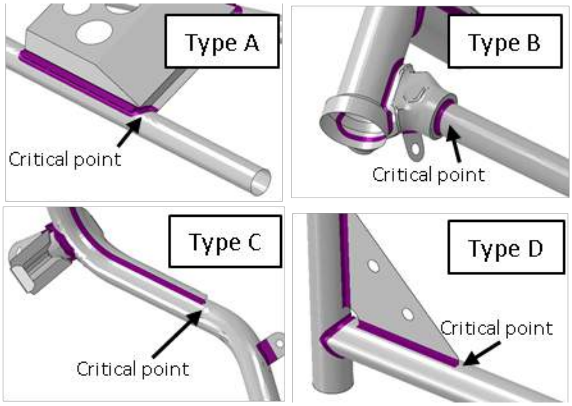


Figure 16. Different motorcycle frame parts with different weld joints.

Other parts of the frame were also created. Figure 16 shows the different geometry with their corresponding finite element mesh models. These are also tested to see if life correlation for different geometry are within acceptable margins. At the same time, to show the difference between hot spot stress method and Verity method. Figure 17 shows the results for both Hot Spot Stress and Equivalent Structural Stresses. As can be seen, the master S-N curves for Verity shows less scatter and gives good correlation to the experimental results.

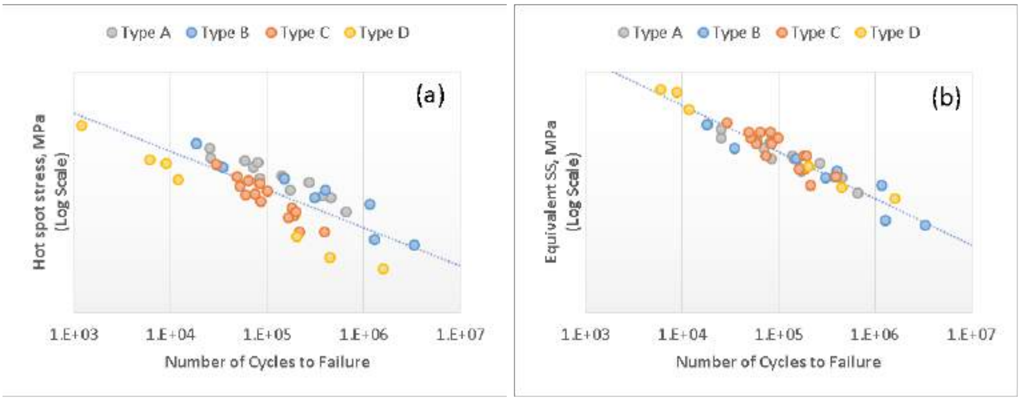


Figure 17. a. Hot spot stress results for different types of parts (different weld joints) b. the corresponding Equivalent Structural Stress.

6. Rough Road

Figure 18. A sample of road profile.

Durability test is needed to be performed to most vehicles. Virtual tests is usually done during design phase and there are many types of loading road histories. One of the more commonly used road is the Belgian or paved road. Yamaha Motors uses our own proprietary test roads and the rough road loading histories were used here. Figure 18 shows a sample of road profile. Figure 19 shows that the predictions correlate well with actual crack locations.

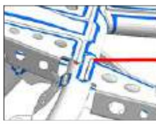
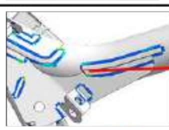
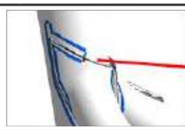
	Prediction	Durability test
Prototype A		
Prototype B		
Prototype C		
Prototype D		

Figure 19. Predicted failure location versus actual crack locations.

7. Development of an automated process

Yamaha motorcycles can contain between 100 to 200 welds and with a total length of 10 meters. Figure 20 shows the welds in a frame in red. Modeling and meshing makes it a very tedious manual process. Verity recommends proper modeling of the welds and also needs input for each weld section (i.e. start node, weld line nodes, weld line elements etc.). Yamaha Motor developed an in house method to create the necessary input parameters for each weld automatically from the bulk data (input data file).

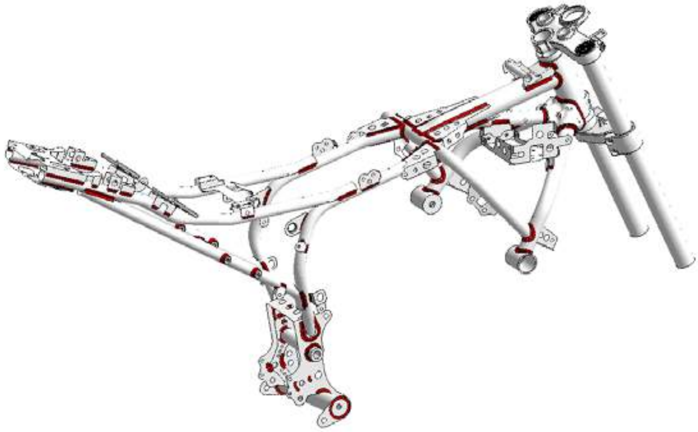


Figure 20. Welds in the motorcycle frame.

8. Conclusion

As can be seen in this research, the Equivalent Structural Stress method of Verity gave very good correlation with experiments and at the same remove the subjectivity in the analysis by providing a mesh insensitive method and no need to choose weld joint type. The results are within standard deviation of ***2***. fe-safe with Verity gave the designers insight on the location and life of the welds in the whole frame. Yamaha Motor is currently using the method outlined here including the automation process to design motorcycle frames.

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10. Acknowledgment

Special thanks to Dr. Alan Tan from Dassault Systèmes K.K. Japan for his advice on welds and fatigue and his continuous support on this project.