Stiffness and durability assessment using different modeling methods of various joining technologies by means of Finite Element Method

Authors: Markus Kaltenböck, Helmut Dannbauer, Klaus Puchner, Christian Gaier

MAGNA POWERTRAIN
Engineering Center Steyr GmbH & Co KG (ECS), Structural Analysis Department
Steyrer Strasse 32, 4300 St. Valentin, Austria
Tel.: +43 (0) 7435 501 324
Email: M.Kaltenboeck@ecs.steyr.com

Abstract

For lightweight automotive body structures, the stiffness and the fatigue behavior is greatly influenced by the properties of its joints. The used joining technology, the number and the distribution of the joints are of high importance to derive a well engineered and cost effective structure.

Since the drastic raise of fuel prices and environmental pollution in the last time the reduction of the vehicle weight is a basic requirement for the development of new cars, trucks, buses or other vehicles. Nevertheless there can be observed a general tendency in the opposite direction. The reasons for this contradiction are on the one hand additional features for more comfort and safety as well as increased engine torques. On the other hand the potential for mass savings in the basic structure is not enormous.

On the market several methods are available to simulate different joining technologies. But it is still often not clear which modeling and assessment method is appropriate for each specific application.

Vehicle bodies have to withstand high dynamic loads while they contain a lot of arc welds, spot joints, bonded joints or other types of joints and notches representing potential crack initiation points.

Therefore, numerical simulations, mainly based on the Finite Element Method (FEM) are state of the art to reduce or even avoid testing loops, prototyping and therefore development time and costs. Nevertheless, release tests are necessary before start of production because of risk considerations.

This lecture will give an overview of simulation approaches for spot welded joinings. The advantages and handicaps of the different available modeling possibilities (fast modeling vs. detailed results) will be represented.

1 GENERAL EXAMINATION OF A BIW DEVELOPMENT

The increasing globalization of the markets and the growing competition in the last decades resulted in a drastic shortening of the product life cycles. Since 1991, the average product lifetime in mechanical components engineering e.g. was reduced from thirty to twelve months [1, 2]. This situation forces the enterprise to shorten the development time and to decrease product development costs. It leads to a conflict situation in which the three aspects development time, development costs and quality assurance interact closely.

The use of modern software such as simulation tools for example, is to find possible counter measures. With their help, comprehensive product knowledge can be acquired at an earlier stage of the development process and therefore cost-intensive errors in later phases can be prevented and prototype cycles can be reduced.

Developments of body in white (BIW) structures are mainly influenced by 3 performance disciplines (crash, NVH, durability). For all these disciplines CAE methods already exist mainly based on the Finite Element Method (FEM). All these simulation tasks are state of the art to reduce and avoid very expensive prototypes and tests. But only with accurate simulation results compared to subsequent tests this savings will become reality.

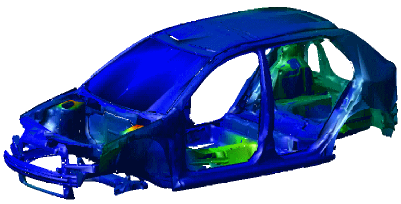


Figure 1: BIW Finite Element model

Beside the meshing of sheet metal panels and the correct computation method one main topic in these simulation fields is the modeling of the joints. Looking into detail there are a lot of different possibilities to realize and simulate different jointing technologies. Especially for spot welds several software houses have created a various number of possibilities to include the behavior of the spot welds more or less detailed.

2 SPOT WELDS IN THE AREA OF FATIGUE SIMULATION

The main goal of the spot weld model in the field of fatigue simulation using the Finite Element Method is to connect the shell elements of the metal sheets and to lead to reasonable results regarding local stresses.
In the first time one was seduced to use one-dimensional node to node connecting elements (beams or rigid elements) to realize welding spots. The problems with mesh density depending stress distribution or high sensibility of the beam forces regarding little inclination deviations of the connector elements lead to the second generation of spot weld models. These modeling techniques with the advantage of mesh independent sheet connections combines more or less the possibilities of quicker mesh generation with more accurate results.

Some examples of the most common connections used nowadays:

Nastran CWELD: Created by MSC together with Volkswagen
CDH/Spot Element: Created by CDH AG. Combination between solid element and coupling elements
Abaqus Fastener
FEMFAT nuggets: Developed by the Engineering Center Steyr / MAGNA Powertrain

For the fatigue assessment of spot welds either the section force of the connector element (force based concept) or the stresses in a well-defined ring of elements around the joining element (stress based concept) can be used.

Within the software FEMFAT (developed and worldwide distributed by the Engineering Center Steyr a company of the MAGNA POWERTRAIN group) both ways are possible.

3 COMPARISON BETWEEN CWELD, CDH AND FEMFAT NUGGETS

This comparison is concentrated to a detailed look to the CWELD elements, CDH spots and the FEMFAT nugget connection.

3.1 CWELD Elements

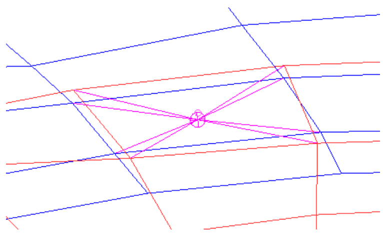


Figure 2: Picture of a CWELD connection element.

Due to the circumstance of a very large distribution of Nastran to solve structural mechanical problems, the CWELD element is often used especially in mid European countries and Japan for BIW developments.
The CWELD element allows connections to be made across components with different mesh densities and with a high grade of automation. Different jointing types (node to node, node to patch and patch to patch) are available.

3.2 CDH/Spot Element

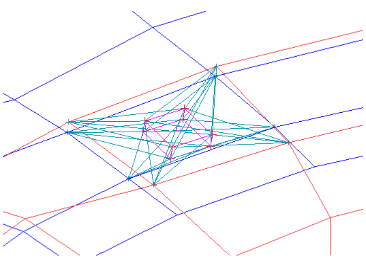
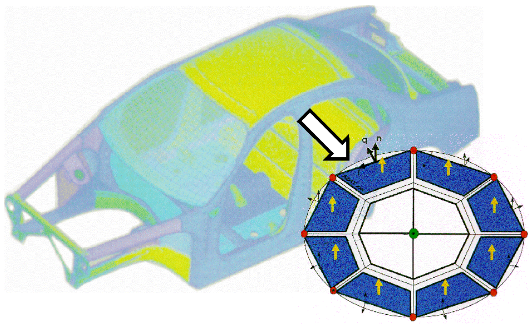


Figure 3: Picture of a CDH connection element

CDH has developed a mesh independent method of generating spot welds. The spot weld is represented by a solid element with the according spot dimension as well as the connection of the solid element with the shell element of the metal sheet by means of coupling elements.

3.3 FEMFAT Nugget

The Engineering Center Steyr has development a possibility of including the spot welds with correct stiffness and fatigue behavior, the so called FEMFAT nugget.
For a FE-mesh without any connecting elements, CAD-Data may directly be imported to generate the spot joint models at the correct location. Otherwise, an on principle arbitrarily meshed FE-mesh but with included connecting elements can be used for remodeling.
A pre-processor is available in FEMFAT which serves to automatically modify the local FE-mesh around the spot welding. The result yields a steady circular element pattern around the spot joint in the magnitude of the diameter of the spot.
Nowadays several common used Finite Element pre-processors are able to create either directly a FEMFAT nugget or are able to extract similar joints which can be fitted to the FEMFAT specifications very easily.



The constant circular FE-mesh around the spot is the basis for a standardized assessment quality of the element stresses, which enables durability results of high quality. Although the total number of elements of the BIW increases the use of modern more powerful computer do not lead to a significant increase in computation time. Quite contrary the benefit of more accurate durability results leads to lower development costs.

Figure 4: Automatically pre-processed local spot joint area of a body in white structure

In the course of automatic generation of the new mesh around the spot joint, the stiffness properties of the elements directly connected to the one-dimensional connecting elements are adapted to correct the singular deformation behavior (see figure 5). In the case of welding spots, Young´s modulus is significantly increased in comparison to regular shell elements. This step leads to a more realistic local deformation behavior, which affects the global stiffness of the overall structure too.

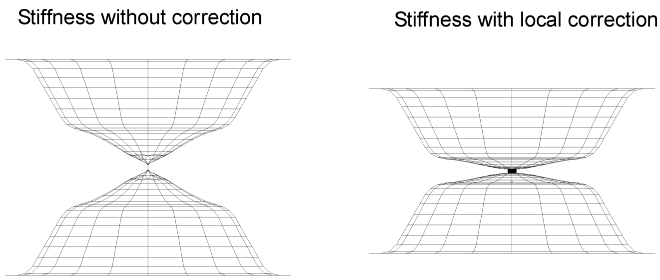


Figure 5: Singular deformation behavior of regular DC specimen (left) and improved deformation behavior (right)

3.4 Stiffness Comparison of different Spot Weld Modeling Techniques

In order to derive correct stiffness results each modeling technique was developed to correspond to test results. But a comparison between the different possibilities shows deviations of the results. In the following the stiffness comparison of DC - specimen similar FE-models is represented in terms of ratios to the FEMFAT nugget stiffness, which were adapted to stiffness tests at the ECS.

3.4.1 FE- models

The FE –models were created to investigate two typical loadcases for spot welded connections.

<u>Shear Load:</u>

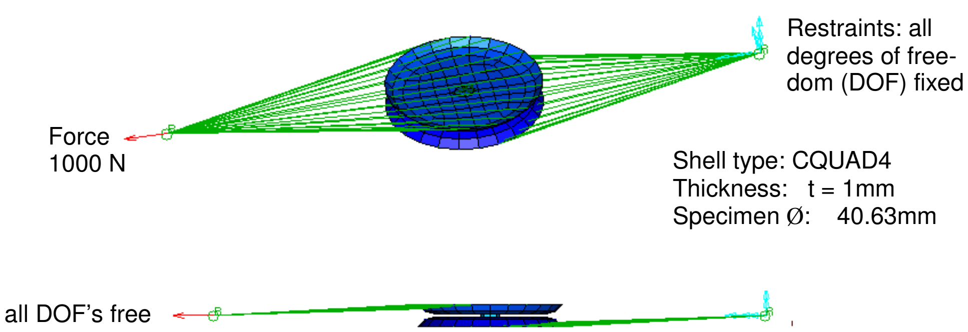


Figure 6: FE-model for shear load stiffness comparison

Beside others upper mentioned modeling techniques were investigated regarding stiffness and compared to the stiffness of the FEMFAT nuggets (set to 100%).

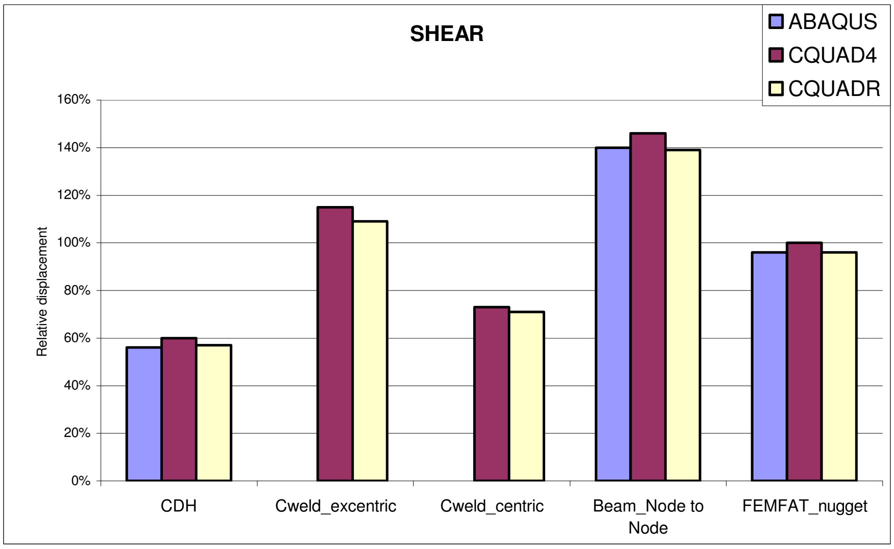


Figure 7: Relative displacement comparison between different modeling techniques in shear direction

One can see that compared to the FEMFAT nugget variations of the spot weld stiffness can be observed. It is a matter of fact that the connection of the two panels using only a simple node to node beam does not represent correct stiffness and results in a too weak connection. The CDH connection as well as the CWELD in a centric position lead to nearly identical displacements while the CWELD connection with excentric connection of the panels looks like much more stiffer. The difference of the excentric to the centric CWELD is the unbalanced connection of the excentric CWELD to the shell elements. Using the new ELPAT function, available in Nastran, this effect can be avoided since this excentric coupling will not occur anymore.

Tension Load:

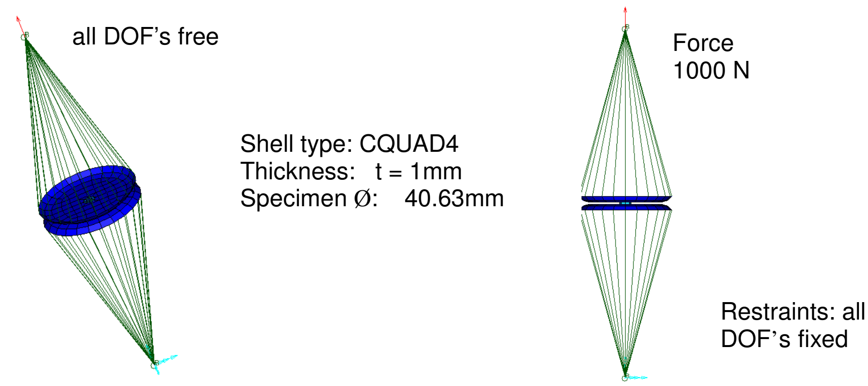


Figure 8: FE-model for tension load stiffness comparison

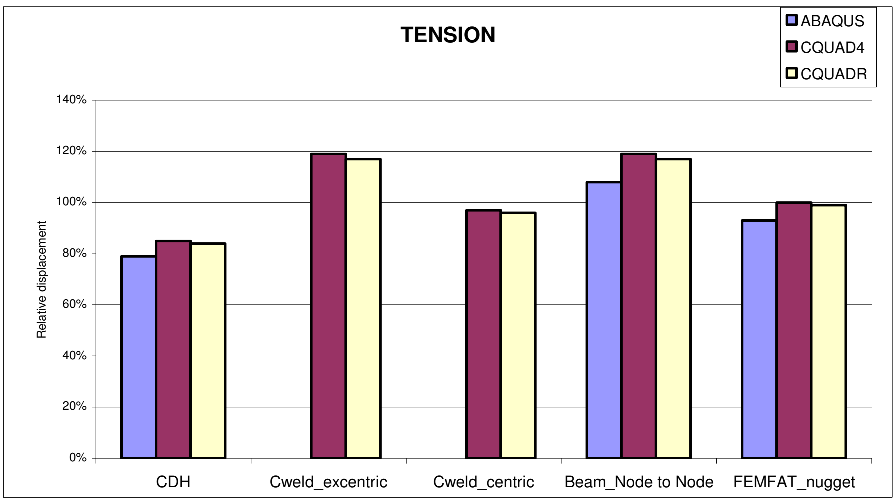


Figure 9: Relative displacement comparison between different modeling techniques in tension direction

In the case of tension load the CDH element again leads to a stiffer connection of the panels. The centric CWELD corresponds good to the FEMFAT nugget while the node to node beam results in approximately 20 % more displacement. The excentric CWELD element is in case of tension loading again weaker than the CWELD in centric position.

3.4.2 Conclusion and Consequences according to the stiffness comparison

Engineers have several possibilities to include spot welds into a FE-model. Each with advantages and disadvantages. For instance the CWELD or the CDH elements connects non congruent meshes and are included in typical BIW pre- processor software packages. These advantages lead to a very quick implementation possibility in the model but the results depend on the base mesh of the sheet metal parts. The usage of the FEMFAT nuggets requires a local remeshing of the structure which leads to a more difficult model change but the results are independent to the basic mesh. Due to the fact that modern pre-processors are able to integrate FEMFAT nuggets nearly automatically the advantage to prevent deviations between variants recommends the usage of the nuggets.

3.5 Durability Comparison

The operating strength of sheet metal parts of bodies is strongly influenced by the properties of their joints. The used joining technology, the design and the position of the welding seams, as well as the number and the location of the spot joints have a significant technical and economical impact. This becomes clear from the fact that in fatigue testing of car bodies more than 90% of the cracks originate from joints [3,4,5]. This is mainly due to the considerably lower dynamic loading capability of welding seams and spot joints compared to the base material. Therefore, especially for lightweight structures, the joining technology plays a key role. An optimum use of the material capabilities is only possible with optimized spot joint design of a structure. This becomes practicable only by assessing the joints in an early phase of the development process.

3.5.1 Different possibilities to analyze the durability of spot welded structures with FEMFAT

3.5.1.1 Stress-based assessment of spot joints with FEMFAT nuggets

Figure 10: H-Specimen for tension peel loading with 10 spot joints and a detailed model of a FEMFAT spot nugget

Independently of the fineness of the shell element basic FE-model new meshes are automatically applied to the local areas around the spot joints before carrying out the FEM analysis. The resulting nugget-like arrangement of elements forms the basis of uniform evaluation quality. In the course of this local enhancement of the FEM mesh, the local rigidities are adjusted to the joining technique (spots welds or self piercing rivets) in use.
The stresses in the shell elements around the spot joint axis are evaluated. Depending on the type of local loading, tension/compression, shear or, more usually, a mixture of the two, different S/N curves are used for the damage accumulation. The shape and sensitivities of these S/N curves were derived from tests on selected test bodies (H - samples and DC - samples) and are provided in a database.

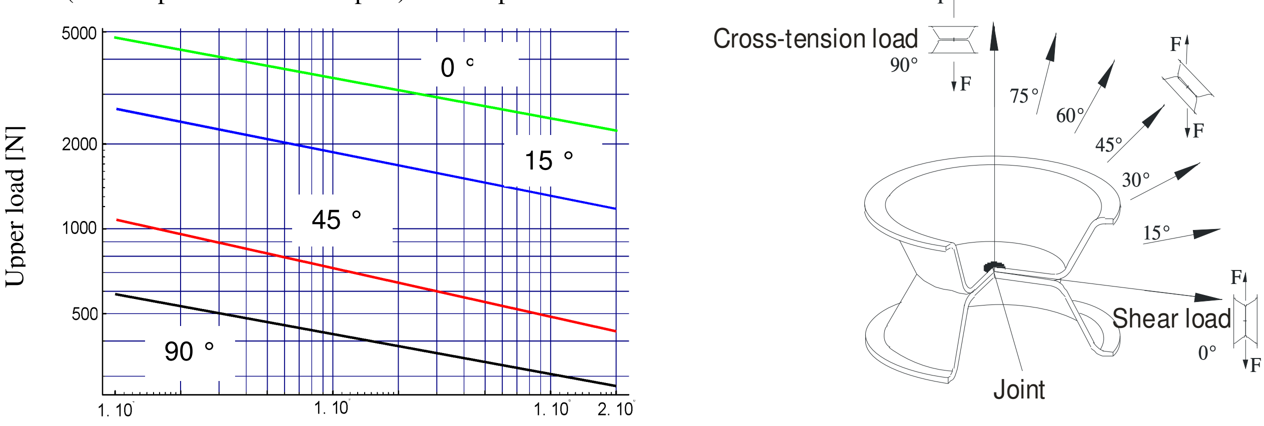
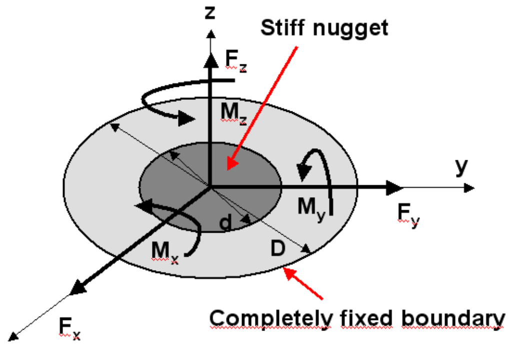


Figure 11: Local spot weld S-N curves implemented in the database of FEMFAT and evaluated with a comparison of simulation and test results of DC-specimen and H-specimen.

3.5.1.2 Force-based assessment of spot joints in FEMFAT

In order to be able to assess spot welds modeled as CWELD's or CDH elements an additional assessment method was implemented in FEMFAT. The internal forces and moments occurring in connecting elements can be used as the basis for an evaluation of the operational strength of spot welds without any alteration of the mesh. The used algorithm accords to the determination of nugget stresses by Nakahara, Takahashi, Kawamoto, Fujimoto and Tomioka suggested in the SAE paper 2000-01-0779 "Method of Fatigue Life Estimation for Spot-Welded Structures" [6].



$$C_B = \left\{ \frac{1-\left(\frac{d}{D}\right)^2}{1+\left(\frac{d}{D}\right)^2} \right\} \frac{6}{\pi \cdot d \cdot t^2} \qquad C_T = \frac{2}{\pi \cdot d^2 \cdot t}$$

$$C_P = \left\{ \frac{\ln\left(\frac{D}{d}\right)}{1-\left(\frac{d}{D}\right)^2} - \frac{1}{2} \right\} \frac{3}{\pi \cdot t^2} \qquad C_S = \frac{1}{\pi \cdot d \cdot t}$$

$$\sigma_{rsum} = C_P \cdot F_z + C_B \cdot \left(-M_y \cdot \cos\theta + M_x \cdot \sin\theta\right) - C_S \cdot \left(F_x \cdot \cos\theta + F_y \cdot \sin\theta\right)$$

$$\sigma_{\theta sum} = \nu \cdot \sigma_{rsum}$$

$$\tau_{r\theta sum} = C_S \cdot \left(F_x \cdot \sin\theta - F_y \cdot \cos\theta\right) - C_T \cdot M_T$$

Figure 12: Calculated stresses due to internal forces and moments of the connection element

3.6 Comparison of durability tests with simulated spot weld results

Since different possibilities are available to determine the durability behaviour of a spot welded structure it is necessary to compare each with test results. As mentioned above the development of the assessment was performed using test results with different specimens. The DC-specimen as well as the H-specimen test results were used to find out a correlation between simulation and real structure results.

<u>Shear Load:</u>

As an example a comparison of the DC-specimen test and simulation result is given in the next picture. The simulation results were derived using the FEMFAT nugget assessment. Different test results were used on the one hand performed at the ECS but coming from OEM investigations too [7].

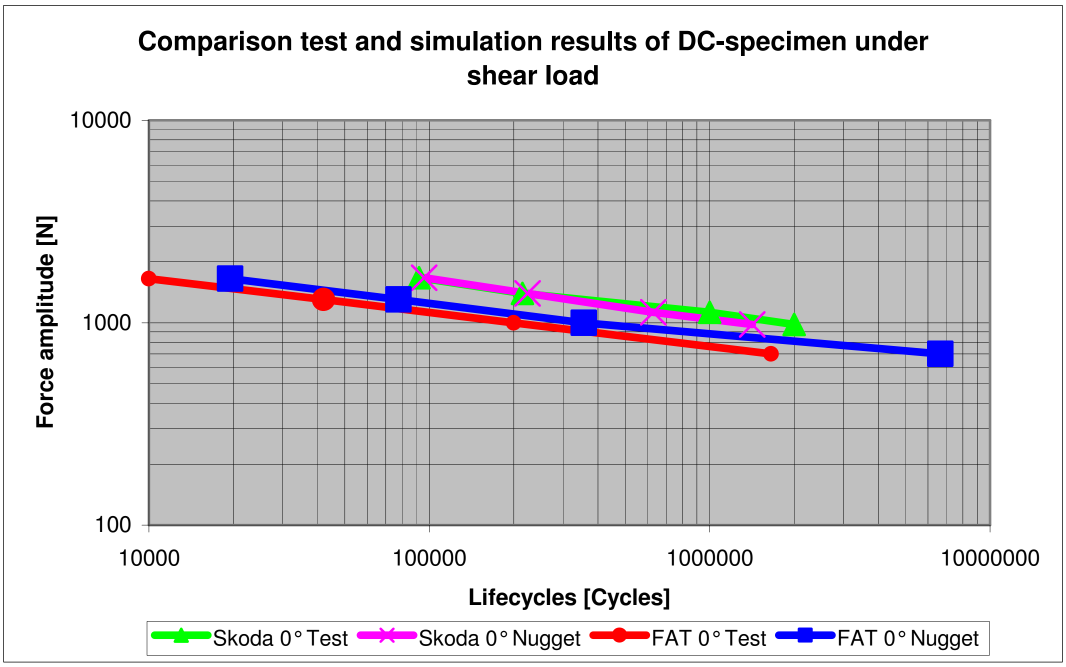


Figure 13: Comparison between test results and durability assessment of DC-specimen under shear load

A good correlation between test and simulation can be found although a the nugget durability prediction of the FAT test [7] is a little bit on the progressive side.

Tension Load:

As well as for the shear load the adjustment of the S-N curves in the FEMFAT database was compared to various load situation. E.g. next picture represents the results of the peel tension investigations of H-specimens. Both possibilities (stress based-, force based concept) are compared to averaged test results.

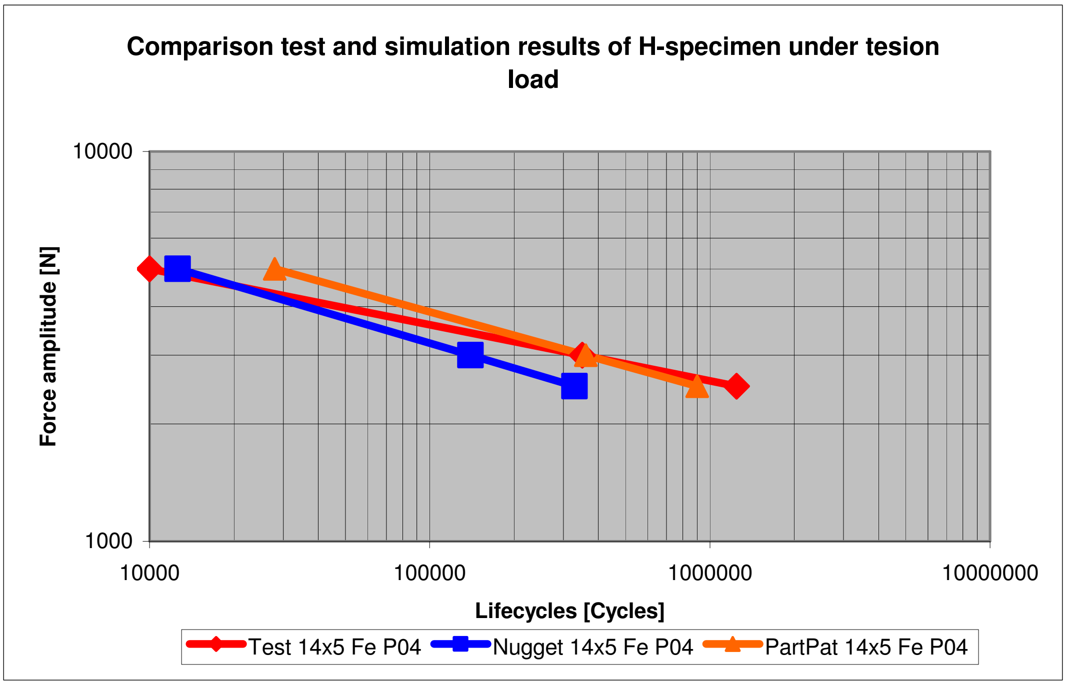


Figure 14: Comparison between test results and durability assessment of H-specimen under tension load

Again one can see that the correlation is quite good. For this example the inclination of the simulated S-N curve does not correspond exactly to the test results. Due to the fact that during developing the FEMFAT module to assess spot welds a lot of tests have been evaluated, we found out that test delivers different inclinations for different structural parameters (sheet thickness, material, spot weld density,..). Within the software FEMFAT SPOT an averaged S-N-curve, taking into account a lot of these test rig results, is implemented.

3.6.1 Mesh influence to durability results

As mentioned before using mesh independent spot weld modeling the basic FE-mesh influences the connection. During creation of a BIW FE-model usually each panel will be meshed separately without any information regarding spot weld location. Although each OEM or structural analysis supplier have their own modeling guidelines, the local element approach in the area of the spot location varies in a wide range.

But it is a matter of fact that the element quality close to the spot weld influences the stiffness, the stresses and of course the internal forces of the spot weld connection element. Without local remeshing, as it is a part of a durability analysis using FEMFAT nuggets, the element quality will influence the durability results significantly.
The following diagram represents formidable the independency of the assessment using the FEMFAT nugget for different mesh sizes. In case of the force based concept (using CWELD – PARTPAT definition) the basic local panel mesh influences the results strongly. I.e. using the mesh independent durability assessment (force based concept) the accuracy can differ when investigation the same part with different meshes.

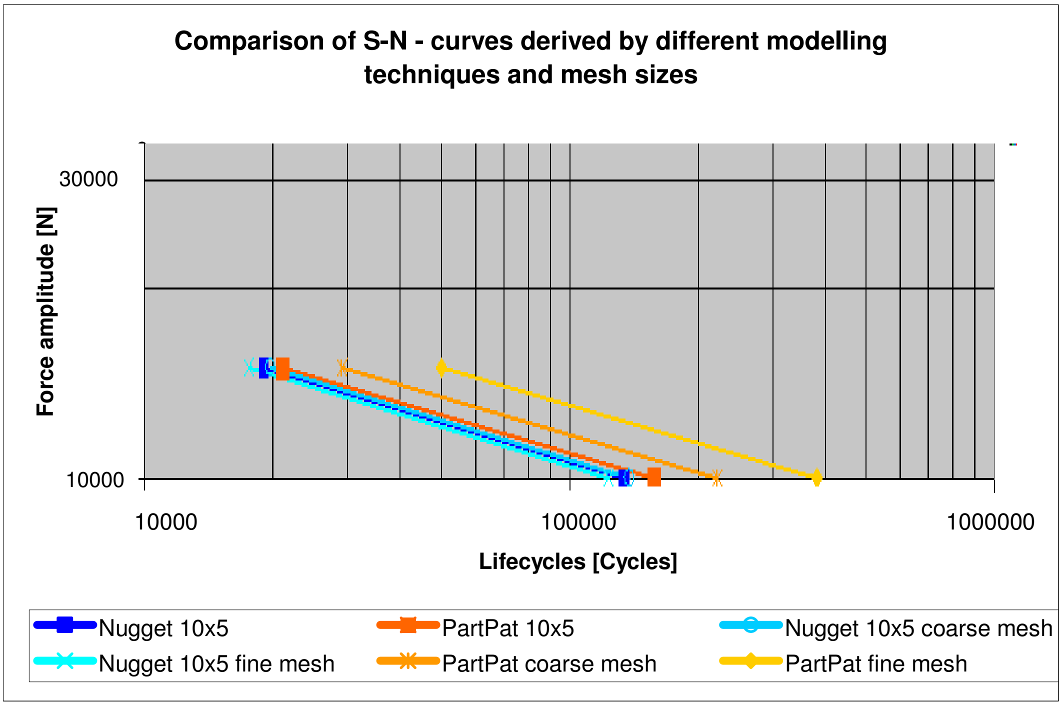
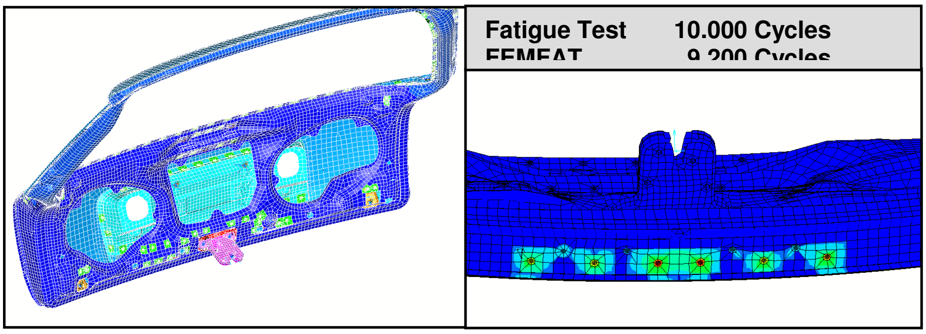


Figure 15: Comparison between durability results of H-specimen under shear load using different modeling techniques and mesh sizes

4 EXAMPLES OF REAL STRUCTURES

The FEMFAT SPOT module was used for a lot of different assessments during real structure development. Beside the usage of FEMFAT SPOT at European and Japanese OEM's many BIW and closure structures were investigated in our house and compared as far as possible to the test results. Some example shall demonstrate the accuracy of the predicted critical areas.

Door analysis:



BIW analysis:

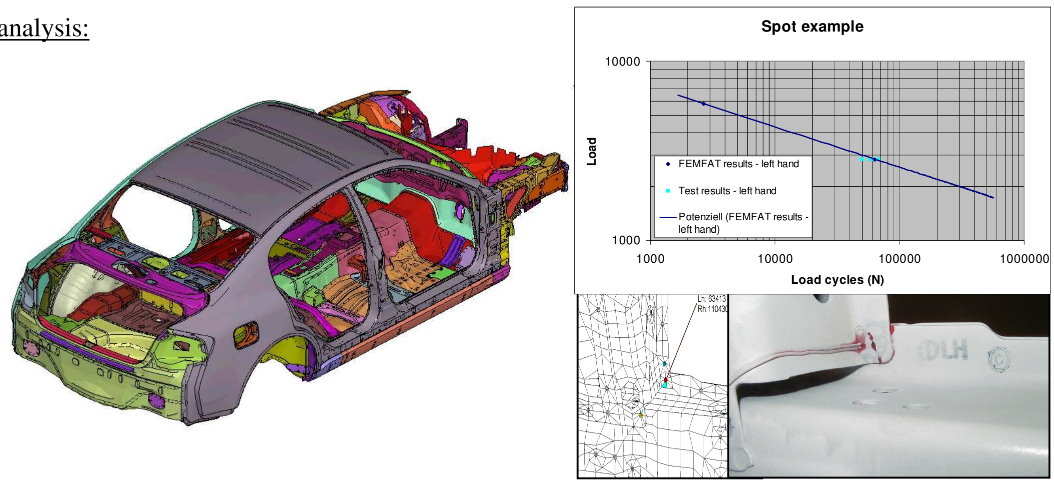


Figure 16: Examples for spot weld durability assessment at real structures

5 CONCLUSIONS

Methods for the implementation and durability assessment of spot joints have been presented. The realization of the concepts within the user-friendly, reliable fatigue software FEMFAT allows a fast and efficient assessment of the operating strength of such structures. The usage and implementation in the development process leads to less tests, shorter development phases, higher quality and therefore less costs.
Two possibilities of fatigue prediction for spot welded structure are available. While the stress based concept requires a local refinement of the mesh in the area of the spot, which can be obtained with an integrated spot remesher in FEMFAT, the force based evaluation uses the internal forces and moments of the connection elements and can be used for non congruent meshes. The results of the nugget evaluation are less sensitive regarding basic mesh size and quality.

Nevertheless due to the pressure to the development engineer to derive quick results of many variants in the beginning of a development the force based concept is very useful. The era of new modern pre-processors which are able to implement FEMFAT nuggets as fast as, for instance CWELDS or CDH elements, leads to the recommendation of using the more accurate and less sensitive stress based method to avoid inconsistencies in fatigue prediction of BIW structures.

Since up to now enormous effects to the fatigue behaviour of BIW structures, like panel contact or damping values of BIW vibrations, can be taken into account with cost intensive effort only, a lot of work is kept left. For the future a lot of further improvements are necessary to derive more precise fatigue results for whole BIW structures.

6 REFERENCES

(1) Fraunhofer IAO Studie 1996

(2) Fraunhofer IAO Studie 2000

(3) Gumpinger, J.; Hahn, O.; Korte, M; Kudrnac, P; Singh, S; Unger, B. (1997) "Computer Simulated Estimation of the Fatigue Behaviour and Stiffness of Spot Joints in Automotive Structures", Proceedings IBEC´97 – International Body Engineering Conference & Exposition, Stuttgart, Germany, September 1997.

(4) Singh, S; Schmid, G; Gao, S. (1991) " Leichtbau durch optimierte Fügetechnik", lecture and paper on the occasion of the DVM Meeting "Bauteil 91" at Berlin, Germany. Proceedings page 239-255

(5) Singh, S.; Schmid, G. (1993) "Dünnblechkonstruktionen und ihre Eigenschaften – Prüfverfahren und ihre Aussagekraft", Special Meeting of the SLV-Munich "Fügen von Aluminium im Dünnblechbereich", Ingolstadt, Germany, November 1993, lecture and paper, Proceedings page 17-26

(6) Y. Nakahara, M. Takahashi, A. Kawamoto, M. Fujimoto, N. Tomioka (2000) "Method of Fatigue Life Estimation for Spot-Welded Structures", SAE 2000-01-0779.

(7) Prof. Dr.-Ing. Ortwin Hahn, Dipl. Ing. Jan R. Kurzok, Dipl. Wirt. Ing. Andreas Rohde (1998) „Untersuchungen zur Übertragbarkeit von Kennwerten einer punktgeschweißten Einelementprobe auf Mehrelementprüfkörper und Bauteile"