

Final report for NI P01039

FE-Design 2003

Improved Usage of High Strength Steel by an Effective FE-based Design Methodology for Fatigue Loaded Complex Welded Structures

Summary.

1.

This project is a continuation of a project with the same name but with project number P98162. The main goal of both projects is to improve the reliability and consistency and reduce the time and effort required to design complex welded structures that are subject to alternating loads. This has been achieved by developing and verifying integrated FEA and appropriate fatigue resistance data including weld quality. Standardised analysis and modelling methods as well as procedures and tools for extracting and interpreting FEA results are analysed. The procedures and tools produced are applicable to generic structural components relevant to several industries that use CAD, FEA, and fatigue analysis.

There have been 26 participants in the project from Sweden, Finland, Denmark, Norway and Iceland. 18 companies, 5 university and 3 research organisations are among the partners. Ten of the companies develop and manufacture fatigue loaded complex welded structures as construction machinery, busses, forest machines, robots, cranes and large ship, 4 are consultant companies and 3 are steel suppliers.

FE-Design 2003 was divided into several subprojects such as modelling and analysing of structures or details. Most of the analysed structures are real structures from the participating companies. Different modelling strategies are addressed and some commercial systems are analysed. In some cases detailed analysis of residual stress fields is performed. To verify simplifications sub modelling or similar techniques is used. Based on the calculated results life predictions are performed (based on different prediction methods). The results are further verified with static measurements and fatigue test on structures where both the life and localisation of cracks are compared. In addition fatigue test of small-scale test pieces manufactured with different weld quality, strength level and thickness are performed. Some of the project results were presented at a large international conference "FATIGUE 2002", in Stockholm 2-7.6.2002. Since several of the project participants is member of IIW the projects results has benchmarked and regularly discussed at IIW events.

FE-Design 2003 - Improved Usage of High Strength Steel by an Effective FE-based Design Methodology for Fatigue Loaded Complex Welded Structures

Project Time 2001 -2003

Participants

There are 24 major participants in the project from Sweden, Finland, Denmark, Norway and Iceland. 17 companies, 4 university and 3 research organisations are among the partners. The last year additionally two organisations joined the project (VTEC and HTU) and Iceland left the project. In all 26 organisations has ben involved in the project. Ten of the companies develop and manufacture fatigue loaded complex welded structures as construction machinery, busses, forest machines, robots, cranes and large ship, 4 are consultant companies and 3 are steel suppliers, se Table 1.

Table 1.

Company/Institution	Company/Institution
(Volvo CE) Volvo Articulated Haulers Volvo Construction Equipment Components, Volvo Wheel Loaders. Volvo Cabs	SSAB Tunnplåt SSAB Grovplåt
Volvo Buss	ICETEC
Volvo Technology (VTEC)	Högskolan Trollhättan - Uddevalla (HTU)
ABB Research ABB Robotics	NTNU (Norwegian Institute of Science and Technology)
DNV (Det Norske Veritas)	DTU (Danmarks Tekniska Universitet)
High Tech Engineering.	VTT (Technical Research Center of Finland)
Richards Concultance	LUT (Lappeenranta University of Technology)
MAN B&W Diesel	Metso Minerals
Alfgam Optimering AB	Rautaruukki Metform
FOI (Försvarets Forsknings Institut)	Timberjack
KTH/Flygteknik	

Project leader: Prof. Jack Samuelsson Volvo CE
Steering group chairman: Prof. Anders Blom FOI
Steering group: Prof. Gary Marquis LUT, Prof. Jack Samuelsson Volvo CE, Prof. Anders Blom FOI, Liese Sund NI

Table 3 gives some key figures about the participants. At least 6 of the active members are delegates or experts within IIW, commission XIII (Fatigue of Welded Structures) and Commission XV (Fatigue Design and Fabrication of Welded Structures).

Table 3 Key figures for FE-2000

62 active participants	18 Companies	6 University	3 R&D org
10 Stress Anal. Dep	9 Doctorate Students	>10 pHD, Lic or equiv.	6 Professors

Technical Results

Introduction

In 1999 a consortium of 24 industrial companies, universities and research institutes representing all Nordic countries initiated a joint research project with the goal developing improved methods and tools for integrating FEA and fatigue analysis for complex welded constructions. Consortium partners represent machinery, construction, manufacturing, energy production, ground transportation and shipping industries. The main objective of the initiative is to improve the reliability and reduce the time and effort required to design complex fatigue loaded welded structures by integrating stress analysis and appropriate fatigue resistance data.

Detailed strength and fatigue analysis is the slowest link in the chain leading from new design concept to realisation. For critical fatigue loaded components, target failure rates are in the range 1×10^{-4} during their economical life. Lack of precision in the fatigue analysis can raise this figure by one or two decades.

Work on the project has proceeded simultaneously along several fronts such as evaluation of existing methods and software, modelling and analysis of complex structures, and quantitative examination of factors influencing weld quality. A majority of the structures considered represent actual components from the participating industries. Different modelling strategies are considered and some commercial systems are evaluated.

Numerical results are further verified based on static or dynamic measurements. In some cases alternate life prediction strategies are used and, when possible, compared to measured fatigue lives. During dynamic testing of structures attention was given to the location and orientation of fatigue damage in addition to the number of load cycles to failure.

Fatigue analysis methods. Over the years numerous methods have been developed to predict the fatigue resistance of welded structures [1-5]. These methods have naturally been developed and verified based on tests of small-scale specimens. A comparison of the four most common methods for fatigue analysis of complex structures is illustrated qualitatively in Figure 1. For example, the nominal stress method upon which most fatigue design codes are based requires the least amount of computational effort but also decreases rapidly in accuracy as structural complexity increases. The geometric or "hot spot" approach is promising for many design situations, but tools for establishing the structural hot spot stress based on finite element (FE) modelling results are not readily available and the method is not suitable for failures initiating from weld roots. Linear elastic fracture mechanics (LEFM) and notch stress based approaches are potentially highly accurate even for complex structures, but the computational effort is currently prohibitive in all but a very few highly safety critical components. Commercial software capable of linking the four methods with FE based analysis is not available.

Stress analysis using commercial FE software has become standard practise in industry. Using FE analysis as a basis for fatigue design analysis usually leads to problems related to the incompatibility of the stress results produced by FEA and those needed for the fatigue design procedures. FEA software is capable of producing stresses at any point in structure with accuracy dictated by the FE modelling accuracy. Theoretically the accuracy increases with the number of elements used. In practise this is true only for geometrically idealised structures having linear material behaviour. Accuracy can be increased but in practice it is limited because of a rapid acceleration in the cost and time required. FE modelling tools are capable of handling complex geometries but short lead-time requirements rarely allow detailed studies.

The aim will be to define procedures and produce tools that are applicable to generic structural components relevant to virtually all industries. The problem is illustrated in Figure 2 which shows a complex welded frame mesh containing over 130 000 elements and has seven load points. Even with this degree of detail the correct stress values for fatigue analysis are not direct outputs from the model. Significant fatigue design expertise is required to first locate critical locations, refine the mesh using appropriate elements and boundary element and then extract and extrapolate the correct stress values [6].

In the past, modelling accuracy has been strongly limited by computing power. This limitation is being constantly reduced but it still exists and currently modelling accuracy dictates the analysis in only rare cases. In the vast majority of industries and design situations the time and resources available strongly limit the analysis to a minimum acceptable level. Trade-offs must be made between accurate global and local modelling and well-defined fatigue analysis procedures are needed to effectively analyse a complex structure such as that shown in Figure 3. This consists of 50 plates, 100 m of weld and analysis is required for more than 20 external loads and moments.

A typical approach in engineering design analysis is to evaluate the stresses in the structural component due to a number of loading situations. For fatigue analysis, an entire history of local stress or strain values at fatigue critical locations is required. These local quantities are related to the global stress values but their calculation is not supported by present FEA software. Fatigue analysis software is currently used by most industries. The main difficulty in interfacing FEA and fatigue analysis software is that it is not usually clear which stress or strain value from the FEA to input into the fatigue analysis software.

Weld quality issues. Weld acceptance limits, such as those in EN-25817, generally relate to what is regarded as good workmanship and focus on easily observed physical characteristics rather than the effect of the feature on structural integrity. This situation is unsatisfactory with regard to fatigue. An example taken from EN-25817 [7] is illustrated in Figure 4. No requirement for weld toe radius is given even though qualitative evidence of the potential influence of weld toe geometry on fatigue strength is available. Well established acceptance standards for welding defects based on fitness for purpose exist but very little progress has been made in linking the fatigue performance of welded joints and weld quality in the broader sense. There is a critical need to link weld quality and fatigue strength especially in the case of welded joints from new materials like high strength steels and welds produced using new joining technologies like high-speed welding.

Fatigue test data can be widely scattered, even when obtained from specimens fabricated from the same steel and tested at the same laboratory, as illustrated in Figure 5. The upper limit life is almost 10 times the lower bound even for this narrow range of specimen dimensions. Such scatter is undoubtedly influenced by variations in weld quality. From the practical viewpoint, design is related to the lower bound fatigue performance, reflecting the very lowest quality tested. A better understanding of the link between fatigue life and weld quality would enable manufacturers to gain advantage in terms of increased design stresses for producing higher quality welds. There would also be both economic and safety-related benefits from a more rational basis for judging weld quality.

For single run MAG welds produced using high-speed equipment, weld profile is not an accurate indicator of weld quality due to the presence of cold laps. A cold lap can be defined as a lack of fusion defect between filler and base metal as shown in Figure 6. Previous work has demonstrated no correlation between weld profile and fatigue capacity for welded joints that contain cold lap defects [8]. High strength steels and aluminium alloys are especially prone to weld toe defects. For many welding processing weld profile can be well controlled

but quality standards must be expanded to also consider the presence of cold laps or other weld radius defects.

In many industries the strategy is to avoid lack of penetration or weld root defects that have the risk of fatigue failure. Fracture mechanics is well suited for handling this type of defect, but involves more work than is normally possible in routine design situations. A library of ready-solved cases is a desirable method for this problem.

Outline of the work

The project has been conducted in primarily in Sweden, Finland and Denmark within a series of 12 work packages. Topics studied within each of the work packages can be grouped generally into four areas: generic structures, complex structures, weld quality issues and critical fatigue issues.

Results and discussion

Generic Structures. The most important exercise in this research area was a round robin comparison exercise for computing hot spot stresses and life predictions for a relatively simple I-beam structure with a welded gusset attachment. Nine industrial companies and research institute performed a total of 28 sets of analyses. It was found that 10% of the analysts did not succeed in correctly computing the nominal stress in the beam. Of the remaining analyses, 20% used shell element and 80% used solid elements.

All those using solid element achieved acceptable results. However, it should be noted that the density of the meshes and number of elements used was, in most cases, very large and can not be considered representative of normal engineering design practice. Only one in five of those using shell element computed a hot spot value close to the “correct” value while all others significantly under-predicted the hot spot stress value. This shows that shell elements still pose significant difficulties for designers. Most analysts used similar hot spot S-N curves but there were some exceptions.

Structural stresses can be obtained using finite element analysis. However, in the initial design stages parametric formulas are desirable for initial sizing. With this in mind, significant efforts was given to defining new parametric formulas and experimentally verify previously published formulas.

A new European standard for welded pressure vessels was reviewed and found to be conservative in all examined cases except for a longitudinal butt weld. Comparison of experimental life and predicted life based on the new standard showed the new code to be non-conservative. However, it is thought that this is partially due to welding misalignment errors.

Complex structures. An important aspect of the project was the verification of various methods based on testing and analysis of complex large-scale components. Five full scale industrial components were selected. These included frames of a timber harvest tractor, a mobile rock crusher, and a wheel loader. An axle stay from an articulated hauler and a crankshaft housing for a large two-stroke engine were also investigated. These structures are shown in Figure 2 and Figures 7-10.

The frame of a new timber harvester was evaluated based on quasi-static FE analysis and dynamic structural simulation using commercial virtual prototyping software. Strain gage field measurements were used to verify the accuracy of the virtual prototype. Fatigue analysis was based on the FE-model using the hot spot method. Modeling of bearing element was difficult in this case and the stiffness of the linear tetrahedron elements was not sufficiently ac-

curate for hot spot stress determination. In most cases the life predictions based on the simulated stress history was shorter than that based on the measured history.

During the analysis of the wheel loader frame, differences between the measured and computed stresses was in some cases very large with the measured stresses being up to 150% of the computed values. These large differences are due to errors in the global FE-model and differences in boundary conditions near points of load input. Simulation of influence of load inputs reduced the difference in the investigation. This study also makes useful comparisons between the fatigue lives computed using different methods. The difference in life prediction based on the calculated results between the four fatigue life prediction methods varies from a factor of three in simple areas up to five in more complicated areas which have significant changes in local stiffness.

For the axle stay the accuracy of the FE-model and the accuracy of predictions methods were of noticeable importance. Difficult boundary conditions illustrated the importance of relevant modelling of an assembled structure. Manufacturing tolerances, in this case, gave large variation on the local stresses. Fatigue failures always initiated from the root side so nominal stress methods and the geometric stress method could not be used. However, even predictions based on the LEFM method were non-conservative by up to a factor of five. In most cases the failure life was non-conservative by a factor of two, which can be considered good for these structures.

Residual stresses in box frame structures for crank shaft housings in large two-stroke engines were studied. Residual stresses were studied both numerically and experimentally and the effect on fatigue strength was determined in the laboratory. These investigations show the possibility of making use of the positive effect of compressive residual stresses in fatigue design of a large welded structure. This was possible because root side cracking is the dominant failure mode in these structures. However, distortion of the structure is a chief concern that needs to be further studied.

Weld quality issues. Important progress has been made in understanding cold laps from both the production and analysis standpoints. This is especially central to the increased utilisation of welded HSS. Stress-life curves for joints with different size cold laps are presented and the results are in excellent agreement with LEFM predictions and fatigue results in an earlier NI-project [8]. The application of Ohta's bilinear da/dN -curve [10] seems non-conservative for low quality joints.

Weld root and lack of penetration defects have been systematically studied numerically and in the laboratory. In Blom [8] the importance of penetration was discussed in connection with fillet welded beams loaded in torsion. Simulations and fatigue tests showed that 1 mm penetration contributed the equivalent of 2 mm throat thickness in terms of fatigue strength. In this paper a 2-D crack growth simulations are performed on several important geometric features and in some cases compared with welding trials. The relative importance of several factors on fatigue strength are quantified. In some cases more realistic 3D-models will be needed.

Critical fatigue issues. When considering the entire life cycle of a welded construction, there are possibilities for increased use of higher strength steels in the design of fatigue loaded structures. Aspects of load spectrum, weld and surface quality must be considered. Reduced weight, thinner sections, and reduced welded costs are some of the potential benefits. Cold forming for rectangular hollow section (RHS) members was considered and a new test method for fatigue testing the cold worked RHS corners was proposed. This can be used in both quality control efforts and the optimisation of the rolling process leading to smaller corner radii. The beneficial effect of plate thickness down to 6 mm was confirmed, but the meas-

ured rate of fatigue improvement was better than that reported elsewhere [2]. No fatigue benefit for 3 mm plate was observed.

Interaction equations for combined normal and shear stresses based on several design recommendations were evaluated. These equations tended to give conservative life predictions but the scatter was significantly larger than that normally observed in uniaxial tests. A damage sum of 0.5 was found to work well for nonproportional loading. Pilot tests using low transformation temperature filler wire for welding have been performed. This work replicates the work done in a number of Japanese investigations [11,12]. Life is increased for constant amplitude loading tests and future tests using variable amplitude loading are being planned.

conclusions

The project has improved the capacity to handle fatigue design of complex welded structures within the participating companies and research organisations. Improvements have been realised but some major questions still remain. Based on the different case studies in the project related to life predictions of complex welded structures, the following preliminary conclusions can be drawn:

- A contact formulation including boundary conditions or meshing approach near concentrated load inputs needs to be developed.
- The combination of shell elements and simplified boundary conditions can result in large error in stress determination.
- From the analyst's point of view tetrahedral elements efficient and suitable for nominal stress determination, but element stiffness needs to be considered in determining correct hot spot values.
- The use of specialised commercial software, related to fatigue design, requires significant expertise on the part of the user to gain satisfactory results.
- To achieve accuracy in life predictions of spectrum loaded structures with LEFM a crack closure model and a residual stress relaxation model is recommended.
- Life prediction of cruciform joints with cold laps based on ΔK_{eq} shows good agreement with test results.
- Thickness effect for welded joints down to 6 mm is observed.

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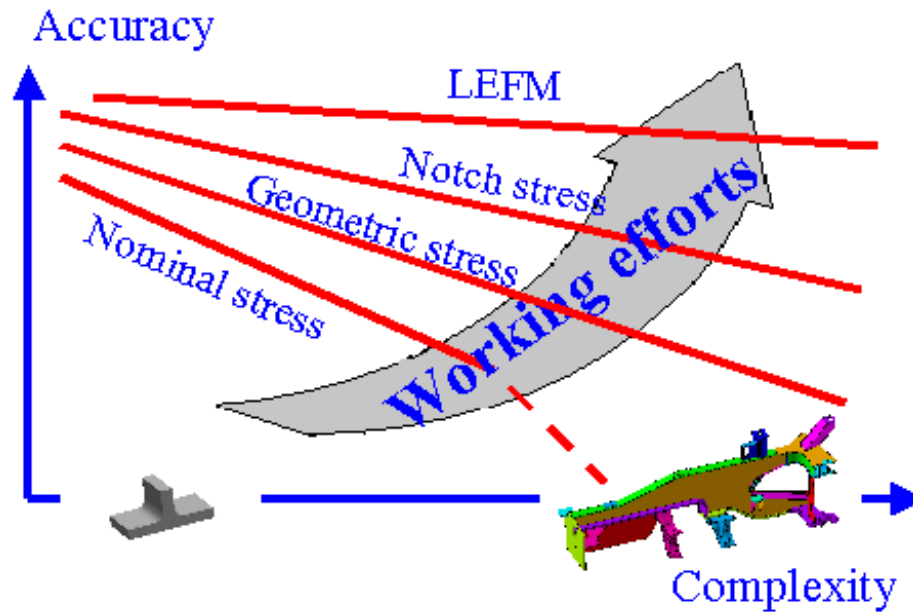
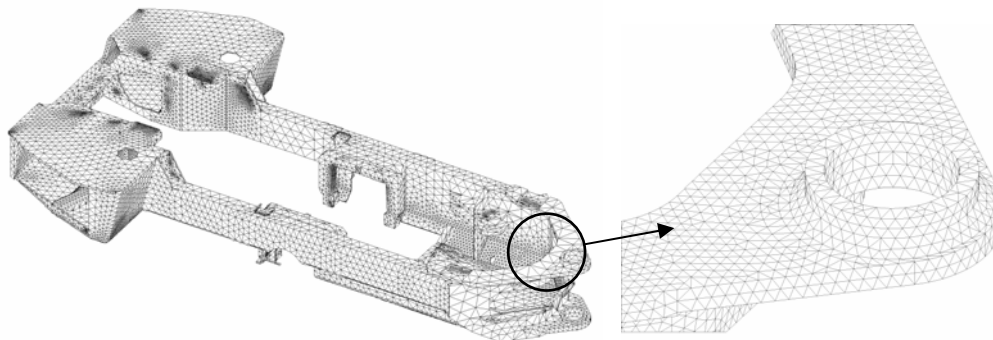


FIGURE 1 . Relation between accuracy, and effort required for fatigue analysis of welded joints as a function of structural complexity.



a)

b)

Figure 2a) Complex welded vehicle frame b) Refined detail of welded bearing house [6].

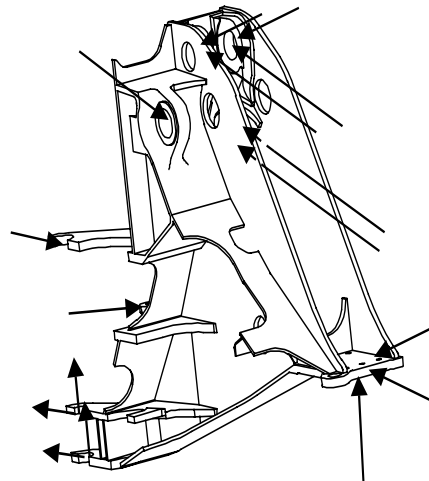


Figure 3 Example of a complex welded structure.

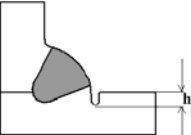
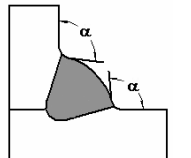
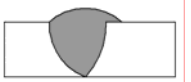
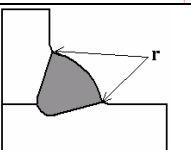
No.	ISO 6520-1 reference	Imperfection Designation	Type of joint	Limits for imperfections for quality levels		
				D	C	B
1.7	5012	Continuous undercut Intermittent undercut		$h \leq 0,2 t$, but max. 1mm	$h \leq 0,1t$, but max. 0,5 mm	Short imperfections: $h \leq 0,05 t$, but max 0,5 mm
1.12	505	Weld toe angle		$\alpha \geq 90^\circ$	$\alpha \geq 105^\circ$	$\alpha \geq 120^\circ$
1.13	506	Overlap		Short imperfection permitted	Not permitted	Not permitted
		Weld toe radius		Not defined		

Figure.4 Weld class examples from current revision of EN-25817 [7].

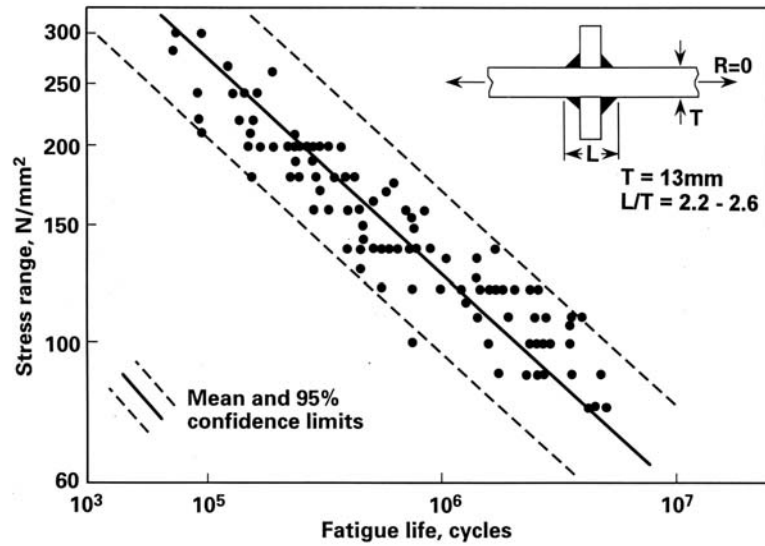


Figure 5 Weld quality has a dramatic effect on observed scatter in fatigue life.

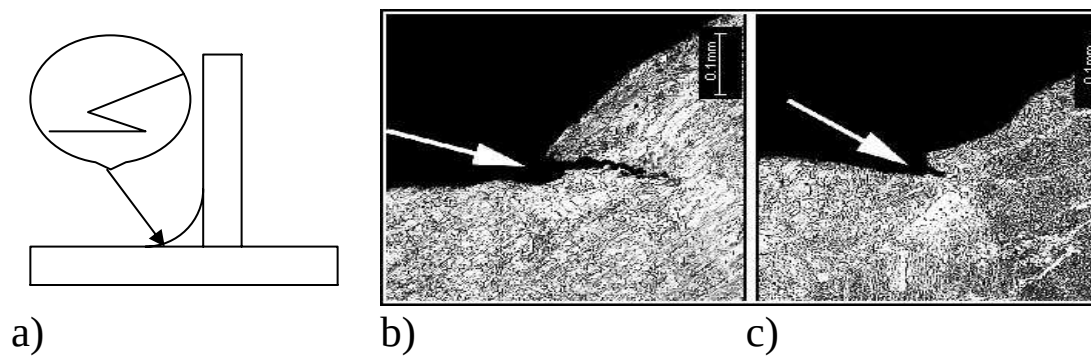


Figure 6. Schematic and photographs of cold laps.

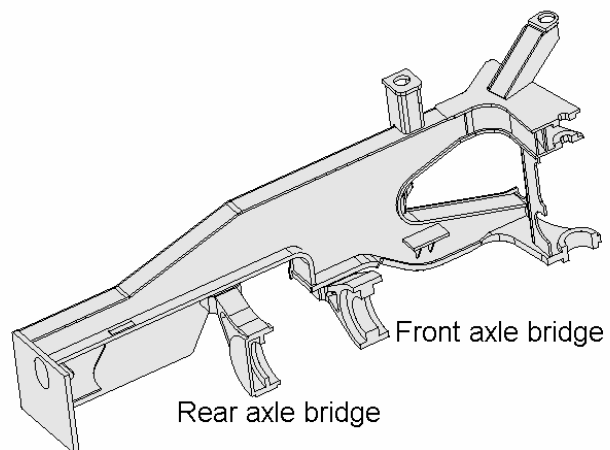


FIGURE 7 Half of a wheel loader rear-frame.

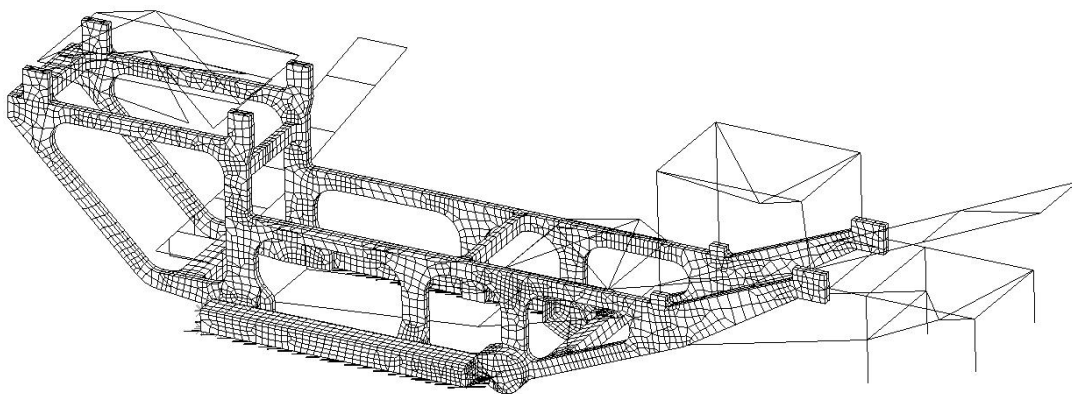


FIGURE 8 Welded frame for a mobile rock crusher.

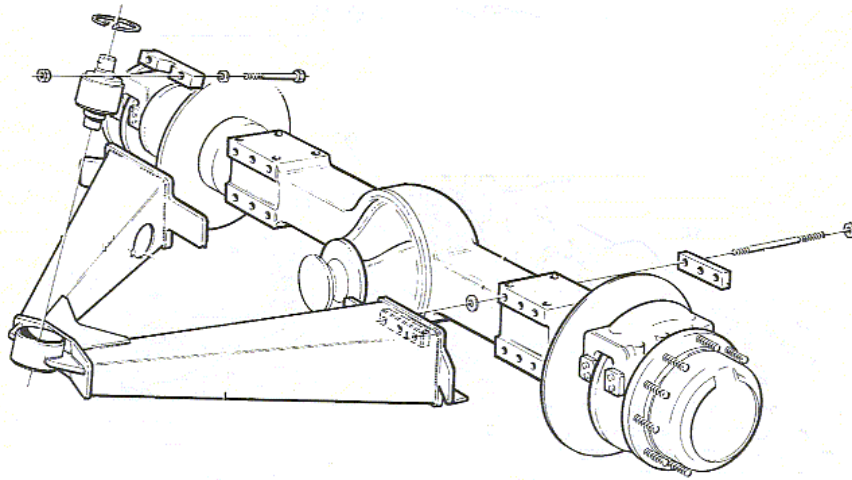


FIGURE 9 Axle stay from an articulated hauler.

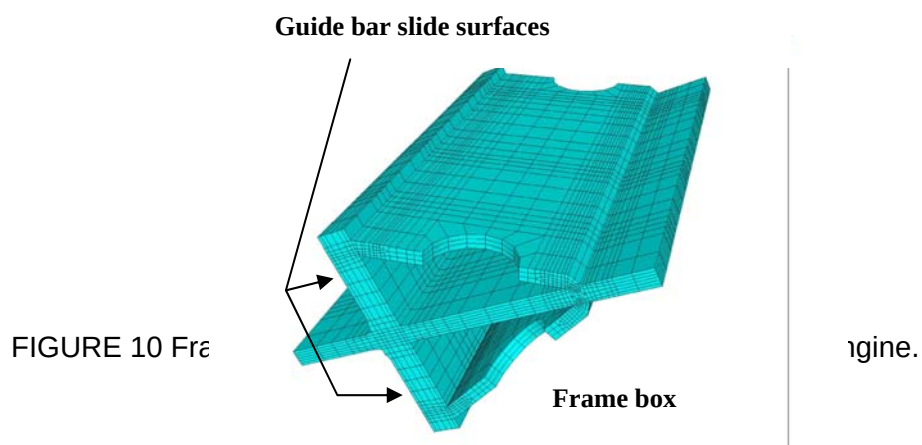


FIGURE 10 Frame

ngine.

Information och resultatspridning

Projektet har sedan 2000 dokumenterats på vår projektweb och f n finnes det ca 60 dokument, Dessutom finns 27 rapporter publicerade i ett proceedings från FATIGUE 2002 (Design and Analysis of Welded High Strength Steel Structures, Ed. Jack Samuelsson, publ. EMAS 2002) I projektet deltagar 10 olika beräkningsavdelningar, 4 konsultföretag samt 3 forskningsorganisationer vilket innebär att värdefulla projektresultat snabbt kommer i produktiv användning i stor skala. Dessutom via de deltagande stålverkens kundservice avdelningar når resultaten även till flera av deras kunder. Projektet har också kontinuerligt presenterats på flera svenska och finska seminarier med 50 - 100 deltagare. Projektet har också presenterats på IIW-möten dels i Ljubljana 2001, Köpenhamn 2002 och Bukarest 2003. I Ljubljana. presenterades 5 IIW-rapporter framtagna inom FE-2000 i Köpenhamn presenterades 6 rapporter och i Bukarest 3 rapporter. I projektet har också 6 examensarbeten publicerats, varav 2 ingår i FATIGUE "2002".

Rapporter

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