DESIGN OF WELDED JOINTS – DETERMINING STRESS STATE

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Abstract: The VDI Richtlinien titled ”*Rechnerischer Festigkeitsnachweis für Maschinenbauteile*” was published by *Forschungskuratorium Maschinenbau* (FKM) in 1998; it provides designers with a design method of a standardized approach on a new basis, even for the stress analysis of welded structures. One of the essential criteria for designing welded seams for static stress and fatigue is knowledge of the stress state in the seam and its surroundings. It is customary to characterize the stress state of welded seams by the so-called *structural stress*. *Erwin Haibach* proposes to determine structural stress along the Haibach line. In our presentation, a brief introduction to the design of welded structures according to FKM will be followed by a presentation of results of FE analyses to demonstrate the use of stresses interpreted along the *Haibach* line as structural stresses. Our research and development activities were performed on assignment by and in cooperation with *Knorr Bremse Hungária Kft.* This presentation is closely linked to the poster presentation titled ”Design of welded joints – calculation of structural stress by numerical methods”.

Key words: *welded joints, design, structural stress, Haibach line.*

1. INTRODUCTION

Basically, FKM design guidelines are calculation algorithms built up in a standardized manner for various cases of application, which consist of rules, calculation procedures, correlations, and factors used for calculations.

The suitability of the component / welded joint examined is demonstrated by the degree of utilization. The degree of utilization is the ratio of the stress (σ) and the limit stress (R) modified by a safety factor:

$$a = \frac{\sigma}{R / j_{erf}} \leq 1 \ , \tag{1}$$

where j_{erf} is a safety factor depending on the structure and the mode of stress. The highest value of the utilization factor can be 1. If the utilization factor is higher than 1 (or 100 %), then the component or welded joint is not suitable in terms of static or fatigue strength.

The following is a discussion of determining the stress state of welded joints.

2. STRESS STATE OF WELDED JOINTS

Welded components should be considered as 2D, surface-like components as the highest stresses are generated on the surface. For surface-shaped structural components, stress analysis / design for fatigue must be performed both for normal stress in directions *x* and *y* as well as for shearing stress in *xy* direction. Therefore, characteristic stress components are:

- in case of *nominal stress*: S_x, S_y, T_{xy} ;
- in case of *structural stress*: $\sigma_{x,max}$, $\sigma_{y,max}$, $\tau_{xy,max}$;
- in case of *effective notch stress (total stress)*: $\sigma_{Kx,max}$, $\sigma_{Ky,max}$, $\tau_{Kxy,max}$.

Figure 1 shows the interpretation of *nominal*, *structural* and *effective notch stresses*. According to the notation in the figure:

S_x *Nominal stress.* Average stress, calculated in an analytical way, using the dimensions of the structure;

$\sigma_{x,max}$ *Structural stress.* Maximum stress generated directly before the welded seam. Extrapolated from the stresses generated before the welded seam.

$\sigma_{Kx,max}$ *Effective notch stress.* A stress taking the impact of stress concentration into consideration: maximum stress directly in the welded seam, calculated with a fictitious radius of r = 1 mm at weld toe or weld root (It can only be used in design for fatigue.)

An example is provided for the interpretation of *nominal*, *structural* and *effective notch stresses* by the welded sheet with a hole shown in Figure 2.

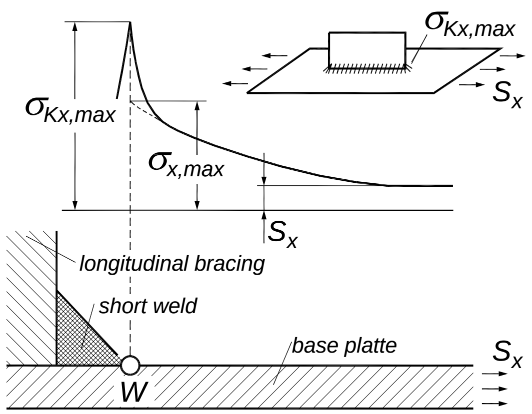


Fig.1. 2D welded component with longitudinal bracing [1].

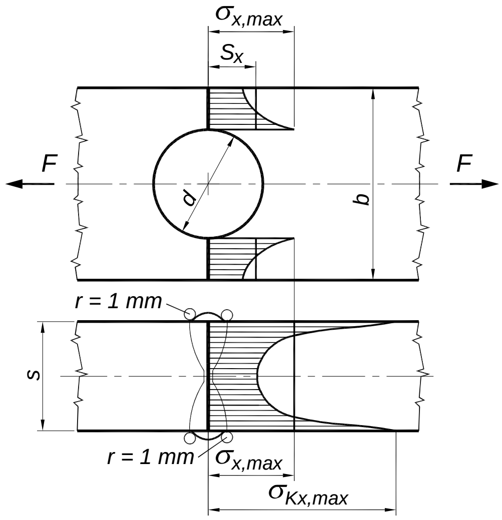


Fig.2. Welded sheet with a hole to interpret *nominal*, *structural* and *effective notch stresses* [1].

The example shown in Figure 2 basically corresponds to a uniaxial stress state, where *nominal stress* (S_x) can be calculated from the actual cross-section:

$$S_x = \frac{F}{(b-d)s} \ . \tag{2}$$

Structural stress ($\sigma_{x,max}$) can be determined by a numerical method, e.g. by a 2D FE method, taking into consideration the impact of the stress concentration at the hole, but specifying stress distribution on a non-welded component.

Effective notch stress ($\sigma_{Kx,max}$) can also be determined by an FE method, but with a 3D model which models the welded seam as well, with the generally accepted fictitious radius of *r* = 1 mm. Let us note again that this stress can only be used for design for fatigue strength.

Based on a literature review, it can be established that the majority of researchers agree that the *effective notch stress state* of a welded seam can be determined by a so-called notched model. In this procedure, the geometry of the component is taken into consideration together with the seam in the course of the calculation, modeling the impact of seam transition by a notch radius resembling the actual welded joint. Practical experiences show that real conditions can be properly approximated by modeling the transition with a radius of *r* = 1mm (Figure 3). Modeling the impact of the stress concentration of the weld toe by means of this radius, the arising peak stresses can be calculated.

Benefits of the procedure include high calculation accuracy and versatility of use. This procedure can be used for determining the *effective notch stress peak* (total stress) at the weld toe.

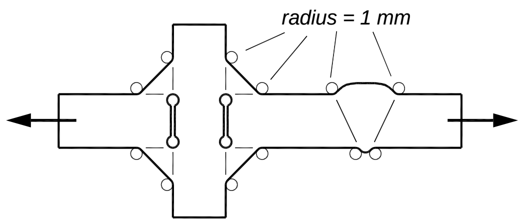


Fig.3. Modeling of weld toes and roots with radius *r* = 1 mm [2].

A disadvantage of this method is that an extremely fine FE mesh is required for calculating the actual stress distribution, which implies a considerable demand of calculation time and disk space, and this may cause serious difficulties when modeling larger-size structures.

Difficulties arising from the application of the *effective notch stress* concept led to the development of the *structural stress concept.* Structural stress is determined by taking into consideration the geometry of the real component, by neglecting the impact of the welded seam – more specifically, by taking it into consideration in a highly simplified manner. The *structural stress state* is determined by an FE model, using a relatively coarse mesh, and stress peaks at critical locations are approximated by the extrapolation of stress distribution.

Structural stress (or hot spot stress) can be determined by the extrapolation of the stresses calculated at given distances from the point of hot spot – at the so-called reference points (Figure 4).

Figure 5 shows the interpretation of structural stress in the case of a butt seam. The hot spots at the top and the bottom side, respectively, do not fall into a single vertical line.

The location of reference points is adjusted to the FE mesh applied. The IIW (2003) proposes the distances of 0.4*t* and 1.0*t* for the distance of reference points from the weld toe in the case of finer FE mesh; however for larger elements the distances of 0.5*t* and 1.5*t* (t is the thickness of the sheet) are recommended.

As regards designing for structural stress, the shaping of the seam, its technology – meaning, in effect, the relationship between effective notch stress and structural stress – are taken into consideration with an FAT (fatigue class) qualification defined by a number of fatigue tests.

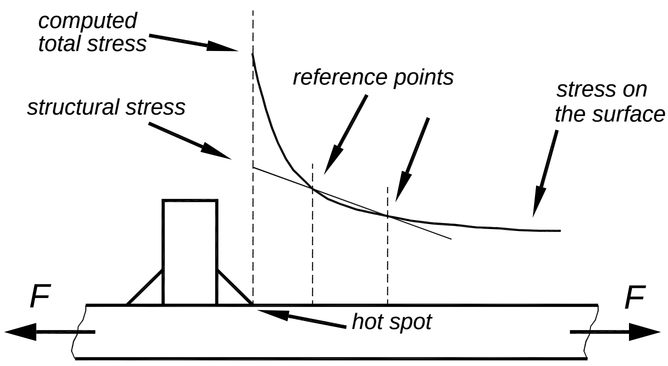


Fig.4. Determining structural stress for butt seam [2].

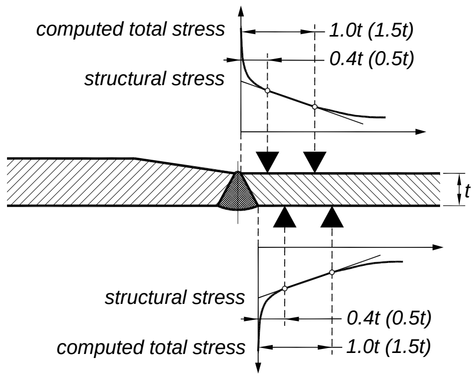


Fig.5. Interpreting structural stress for butt seam [3].

In order to determine structural stress by extrapolation, stresses must be selected at two or three reference points (or along such lines parallel with the seam). (Figure 6.) *E. Haibach* proposes a point (or line) from the weld toe where the calculated stress yields directly the structural stress [6]. Figure 7 shows the location of the Haibach line compared to the welded seam. The distance D_H of structural stress location from the toe of the seam – the so-called *Haibach* distance – is:

$$D_H = D_H^* \approx 2{,}5\,\text{mm}\,. \tag{3}$$

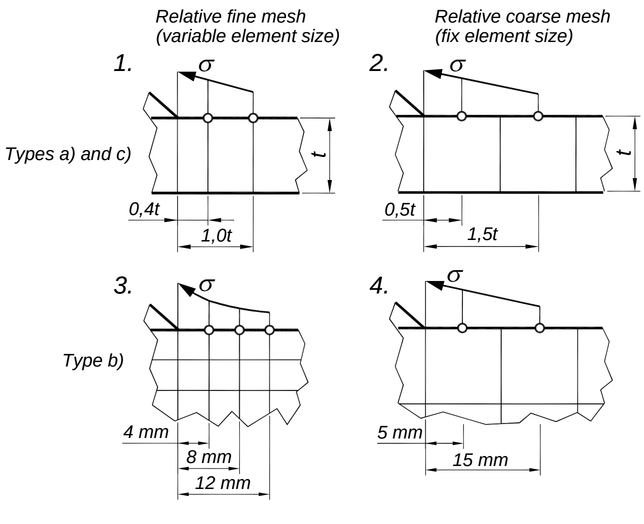


Fig.6. Reference points of various types of FE meshes [4],[5].

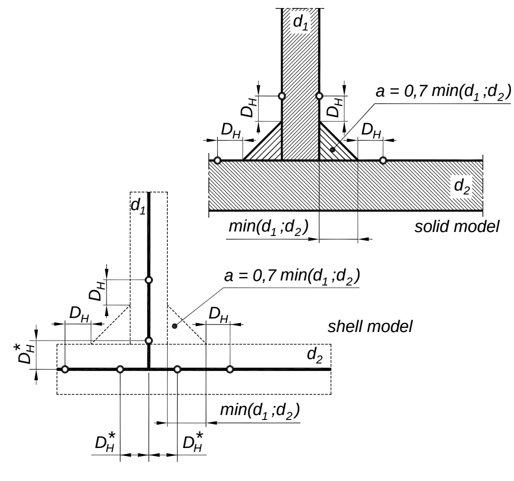


Fig.7. Position of the Haibach lines compared to the weld toe in the case of solid and shell models [6].

In the case of shell models, there is a discussion between the researchers, if the *Haibach* distance is measured from the weld toe (D_H), or from the so-called singularity point (D_H^*). The former is lower by 5-10 %, the latter is higher by 5-10 % than stress calculated by solid model.

A benefit of introducing the Haibach line is that instead of stress selection at two reference points (along two lines) and stress extrapolation, it is only necessary to perform a stress selection at one point (along one line).

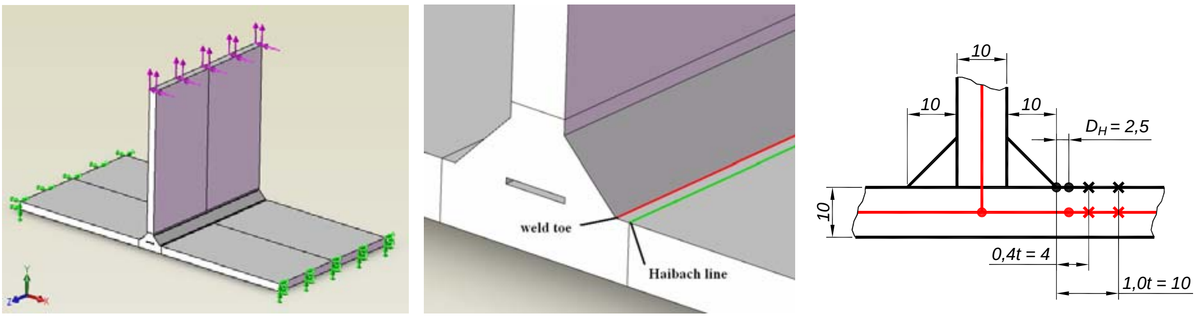
An important task of our investigation is to demonstrate the applicability of the Haibach approach.

3. STRUCTURAL STRESS ALONG THE HAIBACH LINE

The investigation was performed by calculating the stress state of two sheets perpendicular to each other in the vicinity of the welded seam on the basis of various FE models, and by comparing the stresses calculated along the Haibach line with each other, on the one hand, and with traditional methods for determining stresses, on the other hand. It was also examined how the element type, the element size, and the boundary conditions affect the stress values calculated.

Figure 8 shows the geometry, load and boundary conditions of the model examined. Stress query points are also specified in this figure.

The model for determining the effective notch stress state – the so-called notched model – is shown in Figure 9a. The name of the model is Tv1, its FAT classification is 225. The figure represents von *Mises* stresses. The highest stress at the weld toe was 114.3 MPa. For the sake of subsequent comparisions, stresses were determined along the *Haibach* line here as well. Figure 9a shows the effective notch stress field, and Figure 9b shows stresses generated along the weld toe and the *Haibach* line. For numerical reasons, the stress calculated for the weld toe considerably oscillates, whereas the stress rundown along the Haibach line is already undisturbed.



a) b) c)

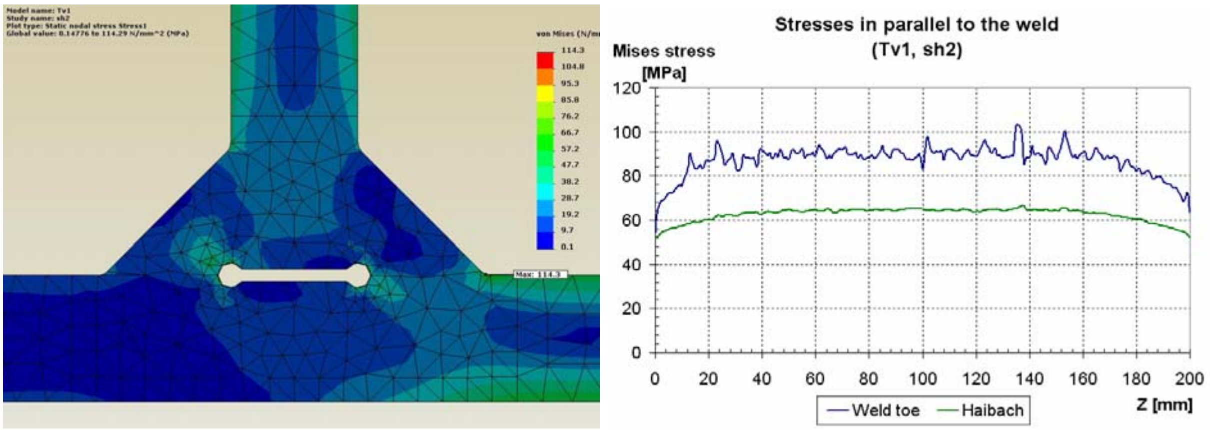
Fig.8. Geometric model for studying butt seam. a) loads and boundary conditions; b) and c) query lines for solid and shell models

The stress state of the Haibach line was studied through 6 types of FE models. Table 1 summarizes the most important features of these models. Mesh density was identical for each model.

The factor S_D is used for comparing the models [1]:

$$S_D = \frac{FAT}{225} \cdot \frac{92}{\sigma_{\max}} , \qquad (4)$$

where fatigue class *FAT* is the characteristic fatigue strength of the detail at $2x10^6$ cycles; *FAT=225* is the stress range or double-amplitude of the fatigue strength at the reference number of cycles of $2x10^6$ and determined experimentally according to IIW; *92* is the specific fatigue limit value of welds in steel for completely reversed normal stress at a number of cycles $5x10^6$ ant it corresponds to *FAT=225* ; and σ_{max} is the highest stress of the line examined (weld toe or Haibach line).



a) b)

Fig.9. a) geometric model to determine effective notch stress (the so-called notched model); b) change of effective notch stress along the weld toe and the *Haibach* line.

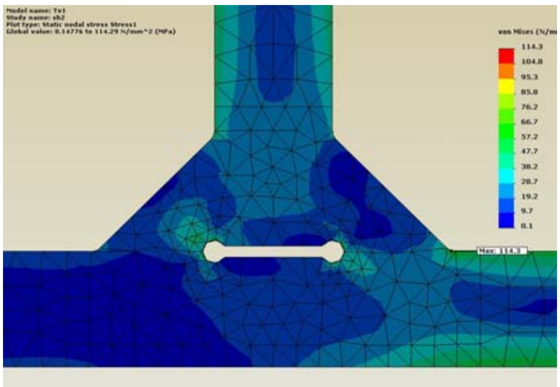
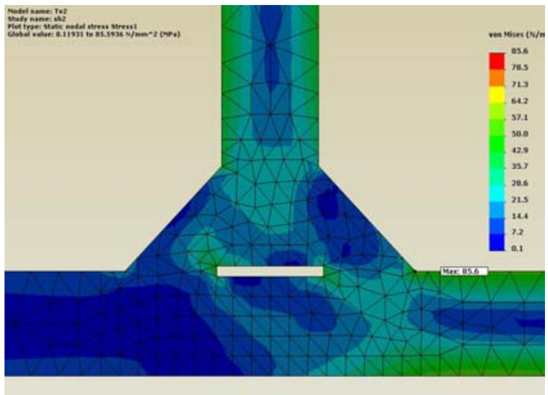
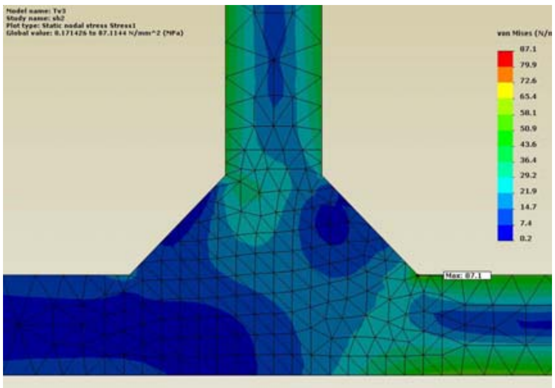
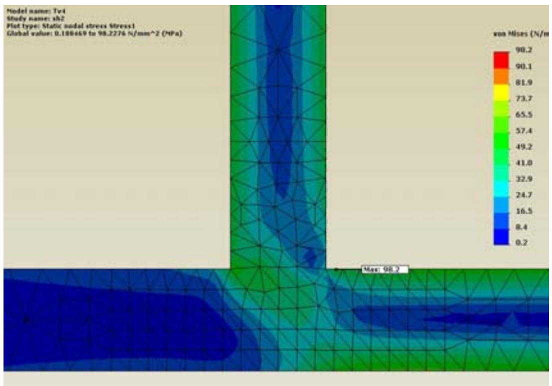
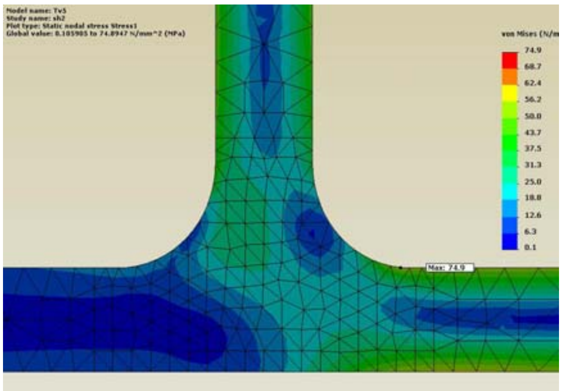
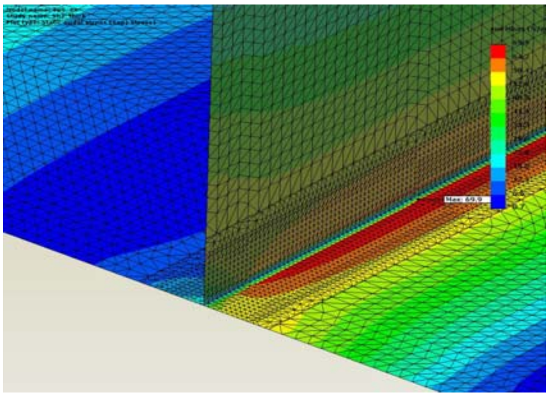
	
Tv1 – S_D = 225/225*92/140 = 0,65 *	**Tv2** – S_D = 100/225*92/65 = 0,63
	
Tv3 – S_D = 100/225*92/65 = 0,63	**Tv4** – S_D = 100/225*92/60 = 0,68

Table 1 follows an the next page.

	
Tv5 – S_D = 100/225*92/62 = 0,66	**TvS** – S_D = 100/225*92/59 = 0,69

* The FE mesh according to Figure 11a is too large to determine the maximum stress. The effective notch stress calculated by reducing the element size is 140 MPa (Chapter 5).

Table 1. Comparison of FEM models based on Haibach stress.

The first model in the table served for determining the effective notch stress. Haibach's structural stress was determined on the other 5 models. The last shell model is intended to demonstrate the applicability of shell elements for structural stress calculations.

Figure 10 shows the equivalent stress distribution of the six types of FE models along the Haibach line parallel with the seam. The figure clearly shows that discrepancies between the Haibach-type structural stresses calculated on various models do not exceed 10%, which demonstrates the applicability of the simpler solid model (Tv4) and the shell model (TvS).

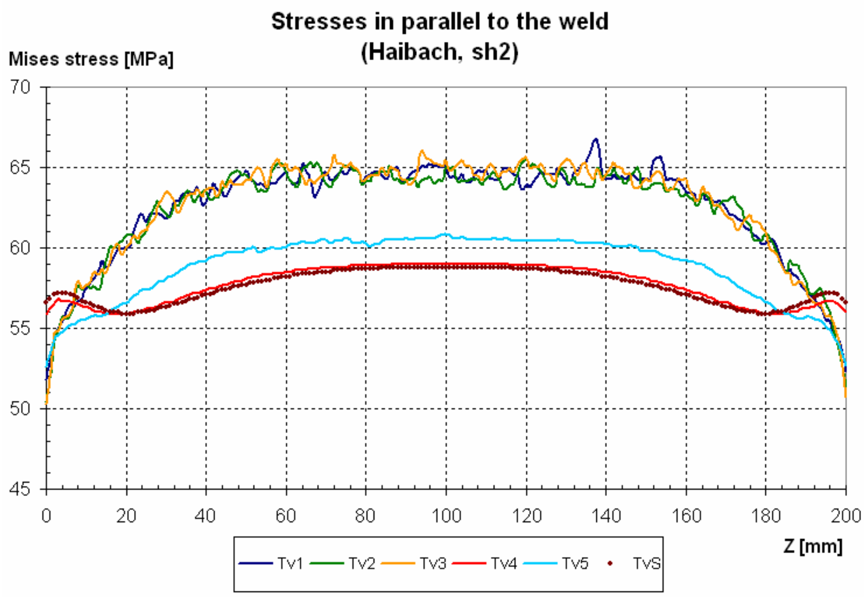


Fig.10. Stress of the six types of models along the Haibach line.

4. COMPARISON OF TRADITIONAL AND HAIBACH STRUCTURAL STRESS

At the Tv3 and the TvS models, the value of structural stress – determined by extrapolation from reference points 0.4t and 1.0t – was compared with the stress calculated along the *Haibach* line.

Figure 11 shows the changes of equivalent stress in the Tv3 model perpendicularly to the seam at the middle and at the edge of the base plate. At the middle of the sheet, stresses were determined at reference points 0.4*t* and 1.0*t* and linear extrapolation was performed from these values to the weld toe. (The extrapolation line is indicated in red in the figure.) The traditionally extrapolated stress was 64 MPa, the stress calculated on the Haibach line was 65 MPa.

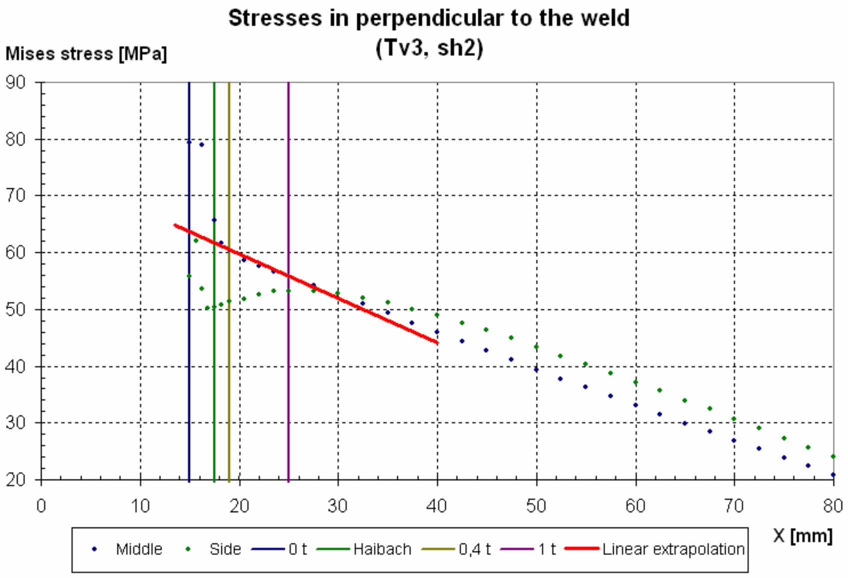


Fig.11. Determining structural stress by extrapolation for Tv3 model.

Figure 12 shows the changes of equivalent stress in the TvS model perpendicularly to the seam at the middle and at the edge of the base plate, together with the structural stress determined by extrapolation at the middle of the sheet. (The extrapolation line is indicated in red in the figure.) The traditionally extrapolated stress was 61 MPa, the stress calculated on the Haibach line was 59 MPa.

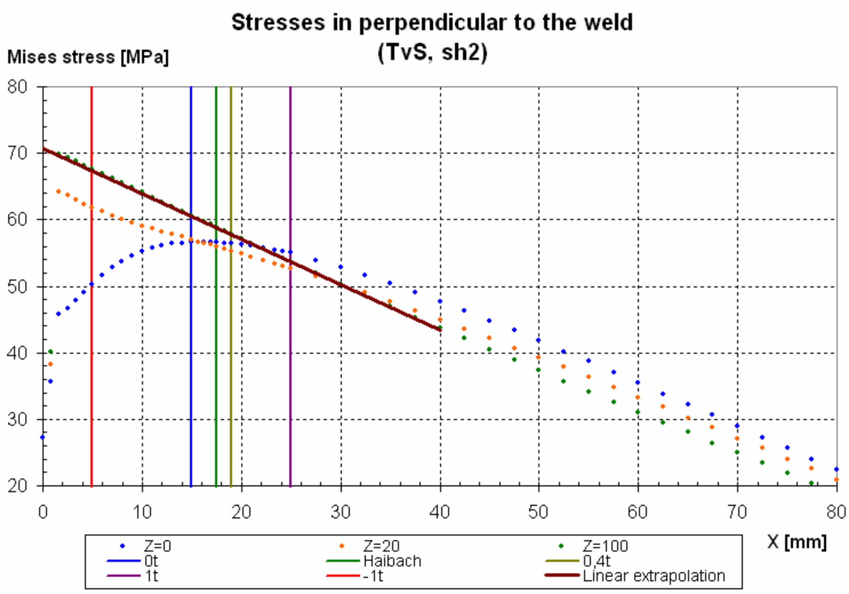


Fig.12. Determining structural stress by extrapolation for **TvS** model.

The value of structural stress determined by traditional extrapolation and *Haibach* structural stress show good correspondence both in case of the simplified solid model and the shell model, demonstrating the applicability of the *Haibach* procedure.

5. STUDYING THE IMPACT OF MESH DENSITY

The impact of mesh density on the maximum stress at the weld toe and the Haibach line was studied on model Tv1. The features of the meshes examined and the results are summarized in Table 2. The outline of each mesh is shown in Table 3.

Mesh	Average element size [mm]	Density at weld [mm]	Number of elements [db]	Max Mises stress [MPa]	Haibach average [MPa]	Element size at weld toe [mm]	Element size along Haibach line [mm]
nh	10	-	13951	84.6	61.3	10	10
sh1	5	-	78959	95.3	61.3	5	5
sh2	5	2	195427	114.3	65.1	2	2
sh25	3	2	387539	114.3	65	2	2
sh3	5	1	801760	122.9	62.8	1	1
sh4	5	0.5 (1) (2)	418239	130.9	63	0.5	1
sh45	5	0.25 (1) (2)	611244	139.6	63	0.25	1

Table 2. Effect of mesh density on stresses.

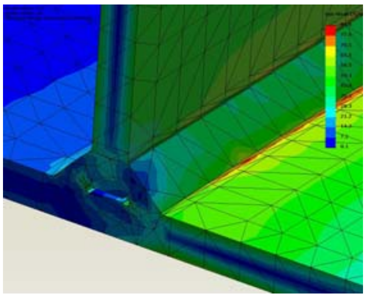
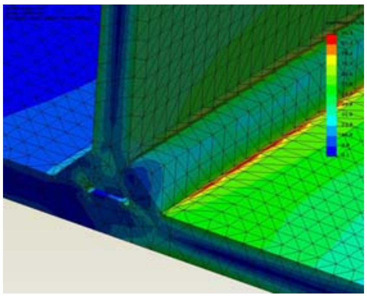
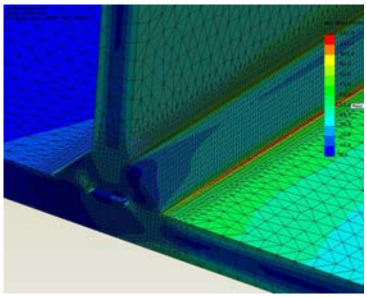
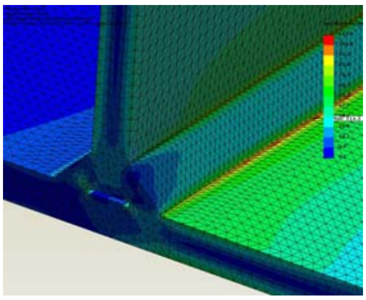
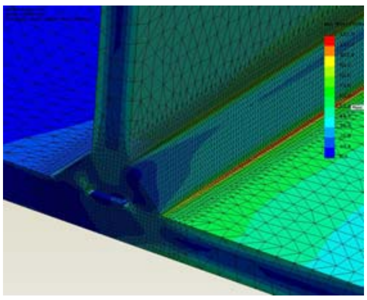
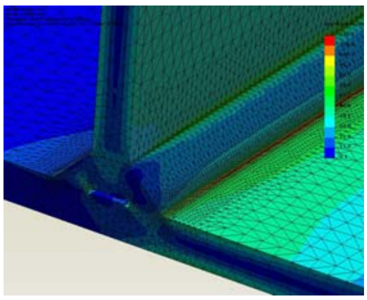
nh	**sh1**	**sh2**
		
sh25	**sh3**	**sh4**
		

Table 3. Mesh structure from Table 2.

Figure 13 shows the changes of effective notch stress and Haibach stress in function of element size. The figure indicates that mesh condensation is expressly required for determining the maximum value of effective notch stress at the weld toe. The 5 mm average element size (sh1 and finer mesh) already properly reflects Haibach stress.

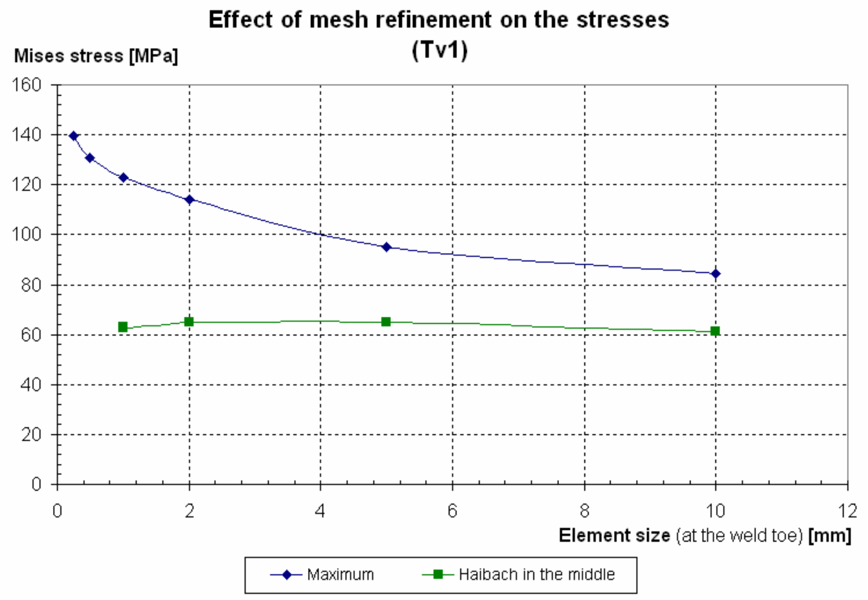


Fig.13. Effective notch stress and Haibach stress at weld toe in function of element size.

6. CONCLUSIONS

Based on the numerical studies performed, it can be established that *Haibach* line stress can be used as structural stress for the design of welding seams. Both the simplified solid model (Tv4) and the shell model (TvS) can be used for determining the *Haibach* stress. The Haibach stress is not sensitive to mesh density.

ACKNOWLEDGEMENT

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