Yield load solutions of heterogeneous welded joints

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Abstract. The effect of yield strength mismatch by welded joints performed with different geometry on the yield load value has been investigated in the context of single edge notched fracture toughness specimen subjected to bending SE(B) using the finite element method (FEM). The crack was located in the centre of the weld. Two geometrical parameters have been identified as most important: crack length ratio a/W as well as slenderness of the welded joint $(W\text{-}a)/H$. They are systematically varied as follows: a/W=0,1; 0,2; 0,3; 0,4; 0,5 and W=2H, 4H, 8H, 16H, 24H. Basic equations and plane strain finite element solutions for the SE(B) fracture specimen with all configuration combinations are given.

This paper aims to establish yield load solutions when the materials inhomogeneity within the weld is present, what usually happen when repair welding is done. For this purpose, practical combination of filler materials, with the same portion of overmatched part with M=1,19 and undermatched part with M=0,86, has been selected. Plane strain FE solutions for the case when the crack is located in the overmatched half of heterogeneous weld were obtained. Effects of different materials combination in the joint were analyzed additionally modeling four combinations: M_{om}=1,19 and M_{um}=0,5; M_{om}=1,19 and M_{um}=0,75; M_{om}=1,5 and M_{um}=0,75 and finally M_{om}=1,5 and M_{um}=0,86, as well. Mismatch yield load solutions for the specimens performed with different weld width have the greatest scattering for the a/W=0,5. The transition from the overmatch to undermatch solution with increasing H is evident. On the other hand, the behavior of the specimen with shallow crack is dictated by the overmatch region ahead the crack tip and depends very little on the weld slenderness.

Introduction

Structural integrity assessment is based on the solutions for limit load and stress intensity factor as well. Today, a plenty compendia are available with mentioned solutions for different structural components [1-3], but none for heterogeneous materials when crack propagate from one to another material through the interface. Such case appears in f. i. functionally graded materials (FGM), which have been strongly developed in last few years using the benefits of the gradual, controlled variation in material composition for dissimilar metal weld applications [4]. This situation is also present in analysis of heterogeneous weld joints, when one part of weld is made from overmatch and second from undermatch weld metal [5]. To estimate the carrying capacity of such performed components the failure assessment diagram (FAD) routine is used very often, but for assessing the crack initiation and growth of the failure within the component using the FAD diagram, it is necessary to find the mismatch yield load F_{YM} solution for the weld component with heterogeneous joint.

In this investigation standard SE(B) specimen with heterogeneous welded joint with I-shaped groove, when one part of weld is made from overmatch and the second from the undermatch weld metal has been considered as the practical example. The aim of this paper is to find the limit load solutions for the welds with different crack lengths and different weld widths.

Limit load solutions for the SE(B) fracture toughness specimen with homogeneous weld

Compendium of the limit load solutions starts from the equation for the plane strain yield load solution when the whole SE(B) specimen is made from base metal [6]:

$$F_{YB} = \beta \cdot \frac{\sigma_{\mathrm{YB}}}{\sqrt{3}} \cdot \frac{B(W-a)^2}{S/2}\text{, where} \tag{1}$$

$$\beta = \begin{cases} 1{,}125 + 0{,}892 \cdot \xi - 2{,}238 \cdot \xi^2 & \text{for } 0 < \xi = a/W < 0{,}172 \\ 1{,}199 + 0{,}096 \cdot \xi & \text{for } 0{,}172 \le \xi < 1 \end{cases} \quad \text{and } S = 4\text{ W.}$$

The base material properties are kept constant, while the weld metal properties vary. This variation is described by mis-match factor:

$$M = \frac{\sigma_{\mathrm{YW}}}{\sigma_{\mathrm{YB}}}. \tag{2}$$

where σ_{YW} and σ_{YB} present the yield strength of the weld metal and the yield strength of base metal, respectively. The weld metal is commonly produced with yield strength having higher values than one of the base plate itself; this case is designated as overmatching (OM) with the mis-match factor M > 1. Yield load solutions for this case are given also in the Reference [6]:

$$\frac{F_{YM}}{F_{YB}} = \begin{cases} M & \text{for } 0 \le \psi \le \psi_1 \\ A + B \cdot \dfrac{\psi_1}{\psi} + C \cdot \left(\dfrac{\psi_1}{\psi}\right)^M & \text{for } \psi_1 \le \psi \end{cases}\text{, where} \tag{3}$$

$$\psi = \frac{W-a}{H},\ \psi_1 = 2e^{-(M-1)/8},\ A = \frac{M+49}{50},\ B = \frac{49(M-1)}{50} - C,\ C = 0{,}3(M-1)\sqrt{M-1}.$$

Equation (3) is the solution for the case when the yielding zone spreads through the cracked section of the weld metal.

However, the increasing use of high strength steels forces the producer to select a consumable with lower strength to comply with the toughness requirements. In this case undermatching (UM), where M < 1 is obtained. In this case the mismatch yield load can be calculated as [6]:

$$\frac{F_{YM}}{F_{YB}} = \begin{cases} M & \text{for } 0 \le \psi \le 2 \\ M\left[\beta + (5{,}384 - 3\beta)\chi^2 + (2\beta - 3{,}384)\chi^3\right]/\beta & \text{for } 2 \le \psi \le 12 \\ M\left[0{,}616\chi + 1{,}384\right]/\beta & \text{for } 12 \le \psi \end{cases}\text{, where} \tag{4}$$

$$\chi = \frac{\psi - 2}{10}.$$

Equation (4) is the solution for the case when the plastic deformation is fully confined to the weaker weld metal, determined from the slip line field analysis.

The mismatch yield load solutions for SE(B) specimen are given in the literature for all possible crack lengths and locations within the weld metal and for both plane strain and plane stress conditions. These solutions where the weld joint is wholly made of either overmatch or undermatch metal will serve as the validation standpoint of the mismatch yield load solutions in the case of heterogeneous weld joint.

Finite element modeling of the SE(B) fracture toughness specimen with heterogeneous weld

In practice, inhomogeneous multipass weld joint with half OM- and half UM weld metal could be used for repair welding of weld joints or in the case when the undermatched weld part should satisfy high toughness requirements, while overmatched weld halves has a crack shielding effect. It is fairly questionable how earlier given yield load solutions for the case of homogeneous weld may be accurately used for a heterogeneous weld. The conservative approach is to calculate the yield load solution assuming that the weld was made wholly from UM. This approach is near to reality for the specimen with a/W=0,5, where the region ahead the crack is undermatched, but considering the shallow crack, it can underestimate the yield load value. Such approach becomes more incorrect with the weld width $2H$ decreasing. Namely, as the weld is narrower, its influence on the complete fracture behavior decreases. Therefore, the yield load values converge to those obtained for all-base metal.

The analysis is focused on the plane strain finite element (FE) analysis of the SE(B) specimen with the crack located in the centre of overmatched weld metal [7]. Plastic yield load solutions normalized by all-base metal yield load are found for the systematically varied widths of the weld as $H=W/2$, $W/4$, $W/8$, $W/16$, $W/24$ and for the specimen consisted from all-base plate. The crack length ratio was changed as a/W=0,1; 0,2; 0,3; 0,4 and 0,5. All combinations are given in Fig. 1, where each key-point associates a suitable FE model.

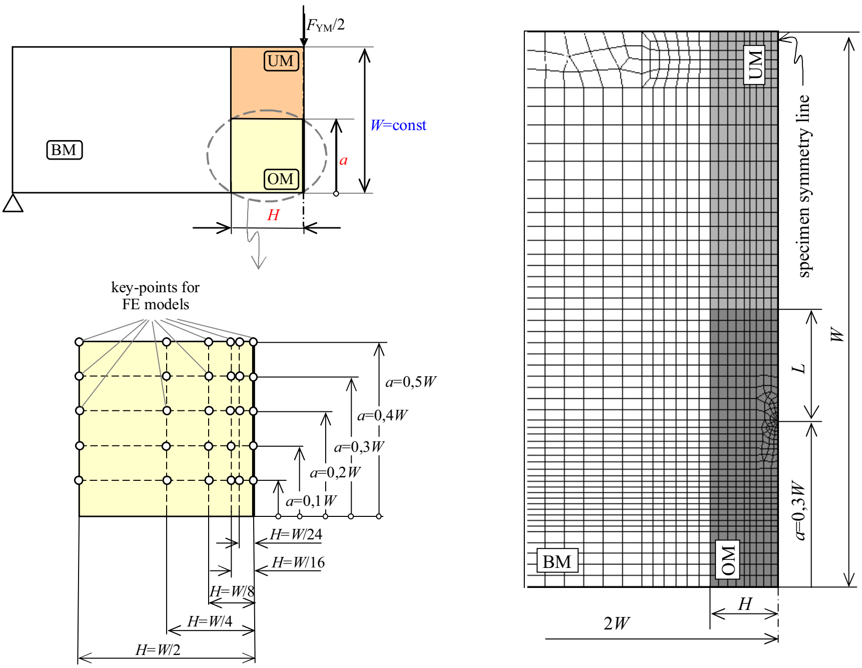

Figure 1: Key-points for total of 30 characteristic finite element models with characteristic mesh

In this work, a practical combination of the overmatched and undermatched weld halves with M=1,19 and M=0,86 with the same portion in the butt weld joint is considered (yield stress of the base metal is equal to 545 MPa). Differences in elastic material properties as well as in strain hardening exponents also play a role. However, in this paper we focused on the problem of degree of mismatch. Detail of the typical finite element mesh with the weld joint with of $H=W/8$, where the crack tip located on the 0,3W is presented in Fig. 1. Butt weld joint geometry was idealized by the strip model, where the zones of heat affecting are omitted. Due to symmetry, only one half of the specimen was modeled. The number of elements and nodes is equal to 1847 and 5690, where the first fan of elements was sized by about 100 µm. All materials were considered as isotropic elastic-almost ideal plastic, with the same exponent of small hardening after yielding point. Plane strain 8-node isoparametric finite elements with reduced integration in order to avoid the incompressibility problems have been used. The magnitude of applied pressure was large enough to bring the specimen to its limiting load state.

FE calculations show that stress concentration close to interface caused additional internal pressure or relaxation along the interface in vicinity of crack tip metal [8,9]. This additional internal stress (positive or negative) can be calculated by using inhomogeneous crack driving force parameter [10]. The additional internal pressure is positive when crack propagates form hard to soft material and vice versa.

Yield load solutions for the SE(B) fracture toughness specimen with heterogeneous weld

The load, which induces the yielding continuously through the ligament, has been observed directly from plane strain finite element analysis. The increment of the increasing load had to be very fine in order to precisely estimate the exact moment of material yielding. Mismatch yield load solutions F_{YM} related to the solution for the specimen made from pure base metal F_{YB} for the SE(B) specimen with different weld width 2H, are given in the Fig. 2 and Fig. 3, depending on the distance between crack tip and fusion line L.

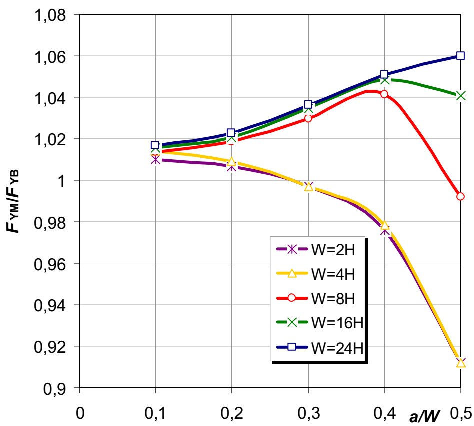

Figure 2: Mismatch yield load solutions for the heterogeneous SE(B) specimen depending on the weld joint width and crack length

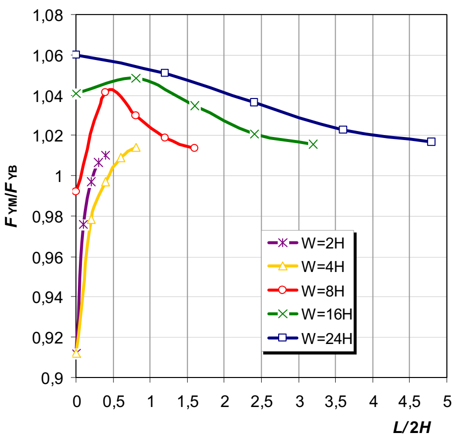

Figure 3: The influence of the distance between crack tip and fusion line L on the mismatch yield load value for heterogeneous weld

Mismatch yield load results are most distinguished for the deepest cracked SE(B) specimen (a/W=0,5 or L = 0) for about 17%. The yield load solutions vary from the overmatch solution for specimens with narrow welds to undermatch solution in the case of welds with low slenderness. Increasing of the inhomogeneous weld width 2H by constant distance between the interface and crack tip L causes the lower yield loads F_{YM}, generally.

It is interesting to see the yield zones of particular materials in the joint, which can be extracted from the finite element results, as it is presented in Fig. 4. There the crack depth ratio a/W was kept as constant as 0,5; while weld root half-width was varied from $H=W/24$ to $H=W/2$.

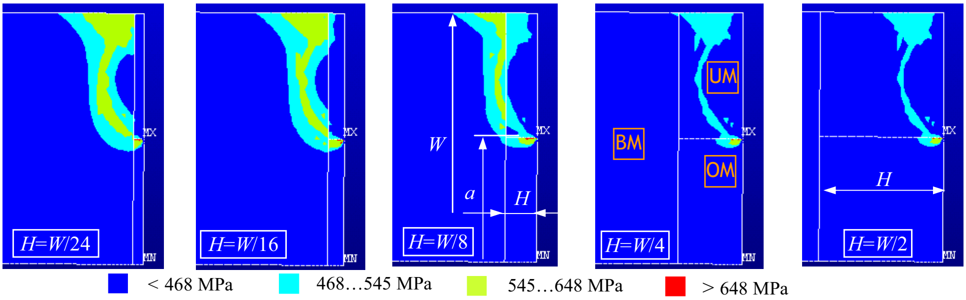

Figure 4: Yield zones shapes for different weld root widths by the constant value of a/W=0,5

It is assumed that the material yields when von Mises equivalent stress overcomes corresponding yield strength of particular material in the joint. At the moment when all materials in front of the crack front yield and yield region spreads from the crack tip to the other side of the specimen, required load for such occurrence denotes calculated yield load value for considered configuration.

To analyze more in details carrying capacity and limit load solutions for welded joints with different geometries and present materials dissimilarity, we done further research varying the mismatch factors of overmatch and undermatch material in the joint. Beside the combination of slightly increased overmatch for 19% (M_{om}=1,19) and undermatch for only 14% (M_{um}=0,86) in the weld, we combined also next four characteristic situations:

a) M_{om}=1,19 and M_{um}=0,5 (difference in yield strength for 69%)
b) M_{om}=1,19 and M_{um}=0,75 (difference in yield strength for 44%)
c) M_{om}=1,5 and M_{um}=0,75 (difference in yield strength for 75%)
d) M_{om}=1,5 and M_{um}=0,86 (difference in yield strength for 64%)

The results for mismatch yield load depending on different materials used to produce heterogeneous weld joint by varying of crack length are depicted in Figs. 5, 6, 7 and 8.

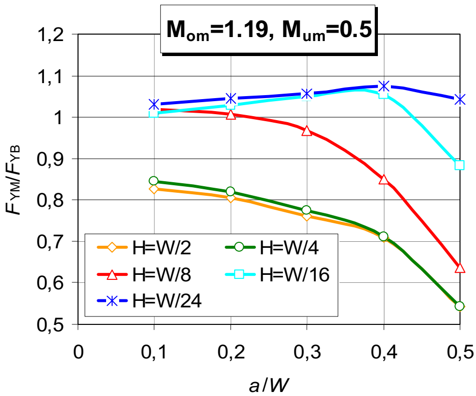

Fig. 5: Mismatch yield load for the weld joint produced with M_{om}=1,19 and M_{um}=0,5

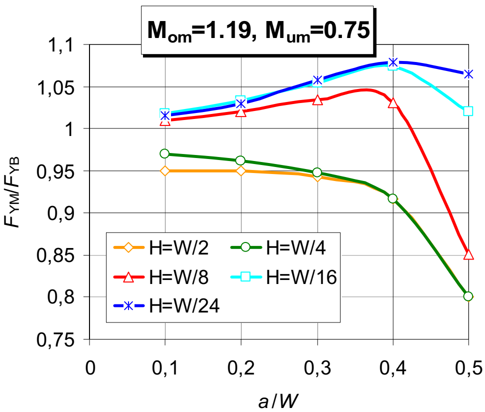

Fig. 6: Mismatch yield load for the weld joint produced with M_{om}=1,19 and M_{um}=0,75

It is obvious from the Fig. 5 that deeply cracked specimens with large weld width and present highly undermatch material ahead the crack front (M_{um}=0,5) have the mismatch yield load with only 55% of the same in the case of all-base material. This could be expected, because yield zones spread easy through the soft undermatch metal. If the weld joint is narrow ($W/24$ or $W/16$), these mismatch yield load solutions have overmatch character, as it is presented on the Fig. 6. In the other hand the influence of the thicker weld width ($W/4$ or $W/2$) contributes to the undermatch yield load solution.

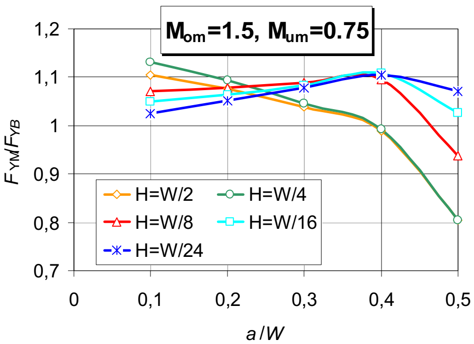

Fig. 7: Mismatch yield load for the weld joint produced with M_{om}=1,5 and M_{um}=0,75

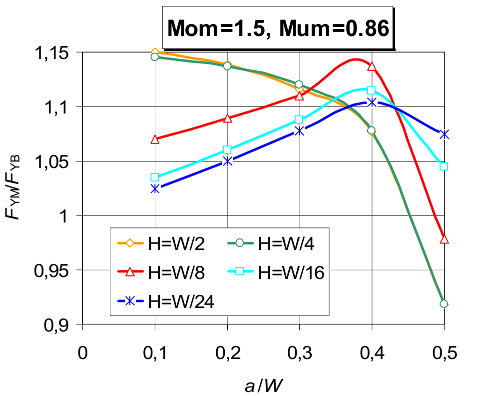

Fig. 8: Mismatch yield load for the weld joint produced with M_{om}=1,5 and M_{um}=0,86

If the crack tip is located in the highly overmatched region as it is presented in the Figs. 7 and 8, all yield load solutions are affected by this overmatch for the crack lengths up to a/W=0,4. It is interesting that mismatch yield load values for the H=$W/2$ or $W/4$ are higher related to those for the H=$W/8$, $W/16$ or $W/24$ up to certain crack length (a/W=0,25 in the Fig. 7 or a/W=0,36 in the Fig. 8), what is opposite to the results given in the Figs. 5 and 6.

The influence of yield strength mismatch degree within the weld on the mismatch yield load value for the maximal and minimal weld width is presented on the Figs. 9 and 10.

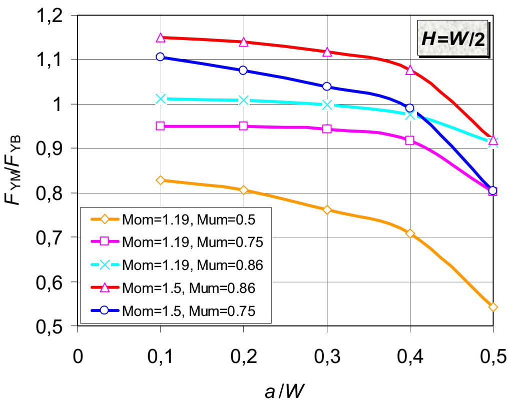

Fig. 9: The influence of the yield strength mismatch degree within the weld on the yield load by constant value of weld width (H=$W/2$)

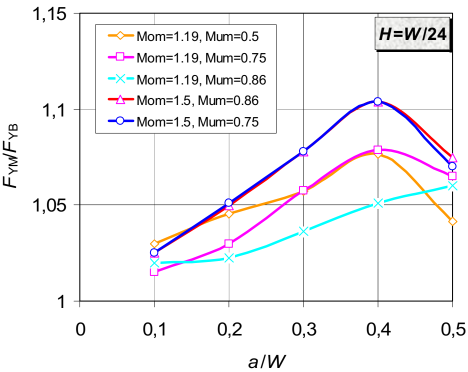

Fig. 10: The influence of the yield strength mismatch degree within the weld on the yield load by constant value of weld width (H=$W/24$)

Undermatch half of the weld dictates that all mismatch yield load solutions for the crack tip located on the fusion line (a/W=0,5) in the weld with the width of H=W/2 (Fig. 9) are undermatch solutions. Mismatch yield loads for different mismatch degrees within the weld decrease almost parallel as the crack increase. As expected the best fracture resistances show the welds with higher value of M_{om}, but also with M_{um} closer to 1. It is also important to remark that all mismatch yield load solutions for the narrowest weld width (H=W/24) have an overmatch character, regardless the crack length, what can be seen on the Fig. 10.

Discussion and conclusions

This paper compiles yield load solutions for the SE(B) fracture toughness specimens with the crack in the centre of heterogeneous weld, where one half of the weld is made as yield strength overmatch and the other as yield strength undermatch related to the base material. Those solutions have been obtained by plane strain finite element analysis. It is shown that the most influencing geometrical parameters on the yielding constraint are a/W and $(W$-$a)/H$ and this is why they were varied systematically in practical range of values.

It is found that in the case of highly constrained heterogeneous weld (a/W=0,5) filled with M=1,19 in overmatched half and M=0,86 in undermatched half, the yield load solutions transit from near undermatch solutions to near overmatch solutions with the increasing of $(W$-$a)/H$ values. On the other hand, the component with shallow crack is less sensitive to the degree of material strength mismatch in the joint. Yielding patterns identifying how the yield regions spread through the ligament for the different widths of weld were also compared. One can remark that material flow ways through different regions of the weldment are affected directly by weld width.

Except this practical combination of the materials in the joint (M_{om}=1,19 and M_{um}=0,86), the mismatch yield load was also calculated for other four mismatch degrees within the weld: M_{om}=1,19 and M_{um}=0,5; M_{om}=1,19 and M_{um}=0,75; M_{om}=1,5 and M_{um}=0,75 and finally M_{om}=1,5 and M_{um}=0,86, as well. The results show that deeply cracked specimens with large weld width and present highly undermatch material ahead the crack front (M_{um}=0,5) have the mismatch yield load with only 55% of the same in the case of all-base material. This is influenced by easy yield zones spreading through the softer undermatch metal. If the weld joint is narrow (W/24 or W/16), mismatch yield load solutions have an overmatch character. For the crack tip located in the highly overmatched region (M_{om}=1,5), all yield load solutions are strongly determined by this overmatch for the crack lengths up to a/W=0,4. It is also notable that mismatch yield load values for the H=W/2 or W/4 are higher related to those for the H=W/8, W/16 or W/24 up to certain crack length (a/W=0,25 in the Fig. 7 or a/W=0,36 in the Fig. 8).

Finally, the influence of the different mismatch degree within the weld on the mismatch yield load by constant weld width was analyzed. One can conclude that welds with the width of H=W/2 have an undermatch character for all cracks with the tip on the fusion line (a/W=0,5), which is dictated by lower strength material on the crack front propagation. Mismatch yield loads for different mismatch degrees within the weld decrease almost parallel as the crack increase. Thereat, the welds performed with higher value of M_{om}, but also with M_{um} closer to 1 achieve better fracture resistance. It is also evident that narrowest analyzed weld width (H=W/24) have an overmatch character, regardless the crack length.

Generally, it can be concluded from the performed finite element analysis that predominant role on the mismatch yield load value play the material properties in the front of crack propagation. This may be the reason why it can be expected that structures with the crack tip positioned in the UM weld part will probably show better resistance to the fracture.

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