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Original Article

Consequences of using overlays on welded joints

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Abstract: The article refers to an earlier publication regarding "reinforcing" overlays on welded joints. In this context, the main principles of designing welded structures were reminded. To verify the principle of not using overlays on the welds, an FEM simulation of such a model was performed. Simulation proved that weld overlays used in plate girder structures are ballast, because they do not participate in stress transfer when tensile is dominant. In addition, they generate a stress concentration in the corner of the pad, which greatly reduces the time to fatigue failure of the structure. A list of the recommendations, requirements for the correct use of overlays on welded joints is given.

Keywords: welding principles; fracture mechanics; fatigue

Introduction

Inspired by the call for discussion by the authors of paper [1], we present our position. Welding, counting from the first patent in this field [2], is less than 140 years old, while fracture mechanics is about 100 years old. Thus, these are relatively young fields of knowledge, science, and technology. Some argue that the perfect weld has not yet been made, and welded structures are not safe in operation. To control several phenomena occurring during their production and subsequent reliable operation, a huge number of documents were developed, which over time were transformed into material cards, technological instructions and then standards - initially industry and national, and finally covering larger areas of agreements. This is how the EN and ISO standards were created, among others.

Catalogue of 34 rules

It should be noted that standards are not sources of knowledge, but documents of known, agreed, and thus often past (not to say obsolete) technical conditions and information enabling the manufacture, control, trade, and operation of welded structures. They are based both on technical data proven over the years and experience, as well as not always justified visions and assumptions of earlier generations of engineers. The latter includes the opinion expressed in [1]: "the weld is the weakest point of the structure". Meanwhile, as indicated by decades of experience in research, production and operation of welded structures, the destruction of a properly made structure occurs not only outside the weld, but also its heat-affected zone, i.e. outside the welded joint [3]. A controversial and constantly developing issue is the concept of "properly made welded structure", which cannot be introduced into any standards, but is an open catalogue of basic, sometimes mutually contradictory rules that should be followed by designers, contractors and those responsible for the operation of welded structures. This catalogue is evidence of the successive acquisition and accumulation of welding knowledge over 140 years. Following work [4], it can be quoted again:

1. Use basic and secondary materials with good weldability.
2. Select consumables for welding (wires and electrodes) with mechanical and chemical properties closest to the basic ones (there are justified exceptions to this rule, e.g. for welding cast irons, chromium steels and steels for work at elevated temperatures).
3. In the case of welding materials with different strengths, select consumables for the weaker, and possible heat treatment for the stronger.
4. Minimize welding operations; use the smallest number of welds with a minimum, only computationally justified volume.
5. Use butt welds instead of fillet welds, because butt welds do not increase the volume and weight of the structure, being only a metallurgical notch. The disadvantage (disappearing) of this solution is the need

to bevel thicker elements included in the joint before welding. Advances in thermal cutting, machining, water jet cutting, and deep penetration welding technologies have been reducing this defect.

6. Use as thin and long fillet welds as possible instead of thick and short ones, because the strength of fillet welds increases with the square and the volume with the cube of their thickness. The thicker the fillet weld, the worse it transfers loads, causes increasing angular deformations of the structure, generating costs, straightening procedures and, as a result, acceptance, and operational problems.

7. Include fillet weld lengths ranging (currently) from 6 to 150 times their thickness.

8. Use butt joints over elbow or T-joints.

9. Do not exceed the limit dimensions of fillet welds: 0.2 g min ≤ a ≤ 0.7g max for one-sided welds and ≤ 0.5 g max for double-sided welds, where g is the wall thickness of the welded material

10. Avoid craters and arc ignition should not take place in the same places of the weld or outside the grooves.

11. Avoid overlapping craters in multi-pass welding (use bead start offsets).

12. Avoid designing joints that must be made in wall, eave or ceiling positions.

13. Minimize the number of assembly joints.

14. Use concave or flat fillet welds (avoid convex) and flat butt welds (never concave).

15. Avoid welding near corners, edges, threads, precisely machined surfaces and after heat and thermochemical treatment.

16. Avoid using any intermediate elements such as: overlays, connectors, etc. (it is recommended to connect the profiles directly butt-to-end, with the shortest possible joint).

17. Profiles should be used with axial loads in the directions of their highest strength indicators.

18. Use spot or intermittent welds instead of continuous welds (exceptions are subject to fatigue exploitation and performed in order to protect the structure against corrosion).

19. Do not design welds in the internal corners of hot-rolled sections, due to the segregation of low-melting components that cause hot cracking.

20. Use deep penetration methods to perform both butt and fillet welds.

21. Avoid crossing joints and their multi-directional convergence as well as points of concentration of tensile stresses.

22. Avoid joints closer than 30mm.

23. Place welds in unloaded or minimally loaded places, remembering that of the two functions performed by welds: joint and load-bearing, the latter should be limited or excluded.

24. Transfer loads from joints to joined elements by using ribs, diaphragms and supports.

25. Strive to minimize the number of different profiles in the structure.

26. Do not allow for tensile loading of sheets and sections in the direction of their thickness.

27. Place welds in technologically easily accessible places.

28. Place welds at or near neutral points or axes.

29. Use smooth transitions in the case of changes in the thickness or shape of the structure.

30. Replace welding with welding, if possible, and welding with soldering (e.g. laser welding is an exception to this rule).

31. Use technological openings in closed structures.

32. Where spot or seam welds are used, they should be loaded with shear forces only, and combined stresses, especially peeling or fatigue stresses, should be avoided.

33. In the case of solder joints - use only lap joints with pure shear loading.

34. Replace resistance welding with friction welding (especially FSW) or other low-energy technologies.

Overlay experience development

The above, incomplete set of construction rules was obtained by trial and - unfortunately - errors, which meant the need to face numerous failures and disasters that affected the manufactured or operated bonded structures. The number of these cases is huge and documented in numerous studies [5-7].

Some, poorly designed and manufactured bonded structures are still in use today. These include building structures such as bridges and viaducts. Figure 1 below shows a fragment of the most famous (now historic) welded bridge in Poland, in which the overlays were used at the end of the 1920s, although they were not rhombic, so they did not give the greatest concentration of stress. For comparison, a modern structure of a welded road bridge (hundreds of which have been built in Poland over the last 30 years) is presented, in which only full penetration welds were used to connect the chords and webs.

a) b)

Fig. 1. History and the present: a) a fragment of the welded bridge in Maurzyce b) a typical road bridge nowadays

The design of the bridge in Maurzyce reflected the then state of knowledge on fracture mechanics. To understand the enormous progress made in this field in the first half of the 20th century, one should look at **Fig. 2** below. A simple list of dates shows that until a certain point the phenomenon of stress concentration caused by overlays was unknown.

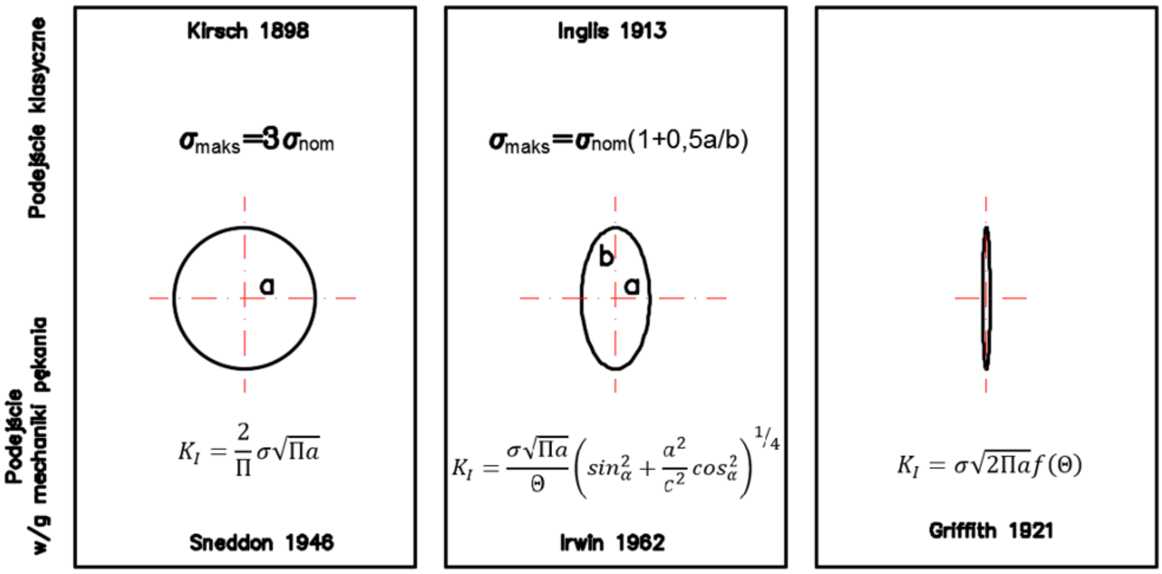


Fig. 2. Development of the basics of fracture mechanics

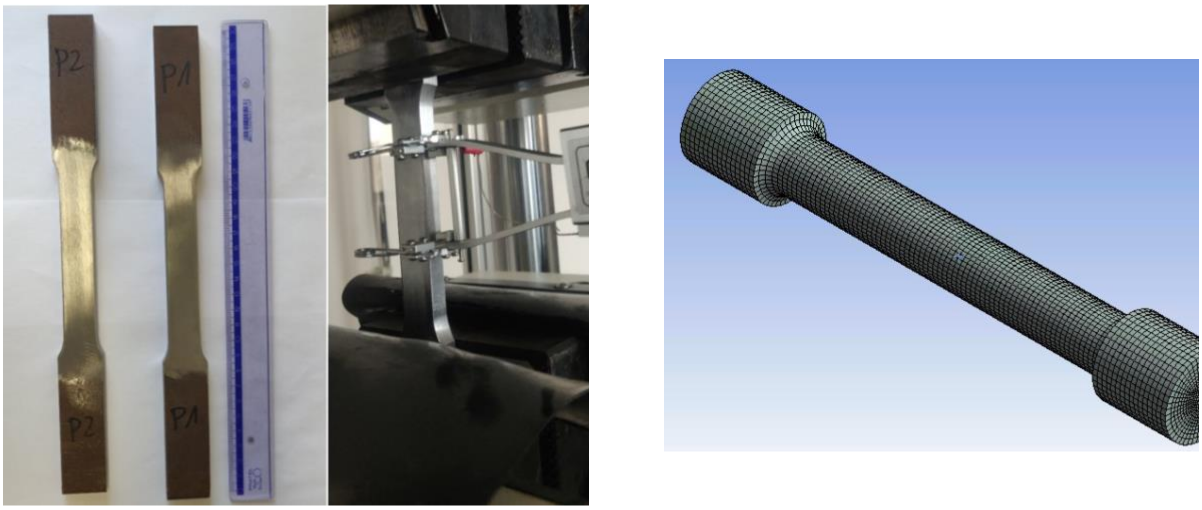
We will not reverse the past, but new constructions must be designed, constructed, and operated correctly, in accordance with the current state of knowledge and computational possibilities, which are provided, for example, by the finite element method. The design and execution practice of bonded structures is constantly struggling with problems resulting from ignorance or disregard of the above-mentioned rules. For example, oversized fillet welds are commonly used instead of using the methods of their calculation indicated in the standard [8] and in works [9,10]. Fortunately, wires and electrodes that are "harder, stronger" than welded materials are chosen less and less often, and structures are "reinforced" with overlays and other unnecessary fasteners. It should be noted that overlays, inserts, additional ribs and diaphragms can be introduced into old structures whose load-bearing materials have been exhausted by corrosion, thermal, thermomechanical or mechanical fatigue processes. However, these operations should be preceded by simulation analyses using the FEM method, because manual calculations may be too inaccurate. The introduction of various types of additional fasteners (including overlays) to welded structures results from inadequate experience in designing riveted structures and is associated with a few unfavourable phenomena, such as:

- unnecessary increase in the weight of the structure,
- unjustified increase in workshop and assembly labour,
- introduction of metallurgical notches and shape into the structure, which leads directly to the formation or accumulation of unpredictable, multi-directional stresses and, as a result, structure fragility [11],
- in the case of leaks between the overlays and the body of the structure - intensifying the course of corrosion processes affecting the places where the gaps were formed.

Below is an analysis of the possible behaviour of nodes with overlays. The following section presents the results of two simulations: the auxiliary tensile test of S355J2 steel and the proper simulation of butt joints with overlays.

Overlay operation simulation

The simulation was performed on a 15-core unit with 30GB RAM and 192GB HHD. The authors of the article had access to the results of the tensile test according to the EN ISO 6892-1: 2020-05 standard for S355J2 steel used for bridge structures. These results were used to create a material simulation program in the database that accurately reflects the behaviour of this steel also in the plastic range. The tensile test simulation model was made in accordance with the normative annex "D" to the EN ISO 6892-1: 2016 standard, which specifies the dimensions of rectangular or round samples. This is shown in **Fig. 3**.



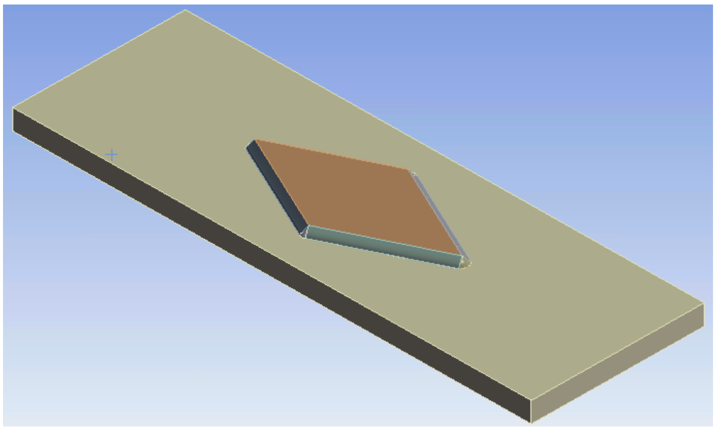
(a) (b)

Fig. 3. Measuring stand and simulation: a) measuring stand, b) simulation model grid

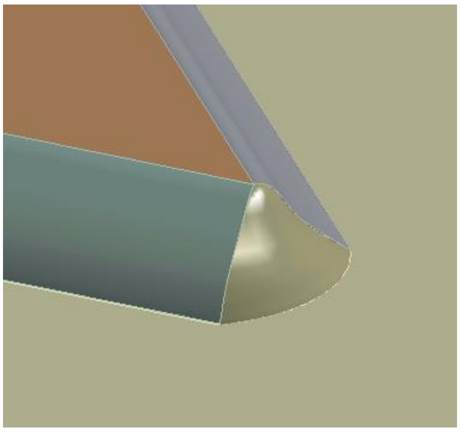
The input data for the simulation program were the actual values of stresses and strains from the laboratory test, which were recalculated based on the general known, simple algebraic relationships connecting stresses and strains, the so-called engineering and real. Since the mathematical model of the material hardening phenomenon used in the simulation program does not tolerate stress drop areas in the plastic range, the stress must be increasing in this range.

The joint model shown in **Fig. 4** consists of two sheets with dimensions of 150x100x12 mm (length x width x thickness) connected in the middle with a butt weld with an X bevel. which was connected to the sheet with fillet welds. Only a single overlay was used because the model is fully symmetric for more overlays. For the purposes of the simulation, it was assumed that fillet welds are made using the 111-process using a typical basic electrode intended for welding low-alloy steels produced by one of the leading Polish producers.

The model was subjected to static load combinations: stretching with a force of 100 kN, bending the end with a deflection arrow of 3 mm and twisting by an angle of 10. In the fatigue combination, the above loads were applied in a pendular manner with the cycle amplitude coefficient R= -1.



(a)



(b)

Fig. 4. Model of a joint with a diamond plate: a) model, b) a fragment of the face of the plate with a fillet weld

Before starting the simulation, the required grid parameters were established. For this purpose, the method of testing the spatial convergence of the mesh was used, thanks to which the optimal type and size of the mesh was determined from the point of view of the precision of the results and the duration of the simulation. The error values were determined by comparing the shift value of the selected node from the simulation with the theoretical shift value determined for an infinitesimal finite element. For the finally selected size of the finite element, the mesh error was 0.9%. Tet10 tetrahedral elements with a linear shape function were used.

Simulation results

Simulation of the operation of a welded joint with overlays showed that overlays in each case are a source of stress concentration (SIF) and reduce the number of cycles to failure. The calculated values are presented in the tables below. Note that the obtained stress values are only valid for the specific angle between the fillet weld face and the plate as shown in **Fig. 3b**.

Table I List of stress concentration factors

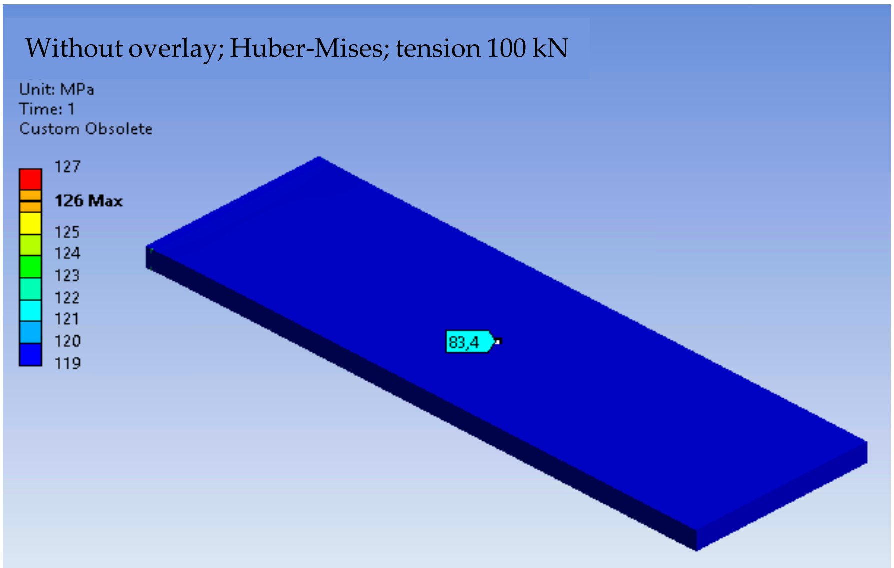
	Tensile	**Bending**	**Torsion**
SIF	359/83=4,3	374/145=2,6	195/97=2,0

Table II List of cycles to failure

	Tensile	**Bending**	**Torsion**
Number of cycles	3783	3322	28234

To limit the size of the article to a reasonable size, **Fig. 5** below shows the results of the simulation in graphical form only for stretching. The results for the joint without overlays were taken as a reference value. The simulations show that in each of the basic load types, the overlaps are the source of stress concentration. Its value depends on many factors, such as: the type of load or the position of the overlay in relation to the restraint points. The contact point between the sheet and the overlay does not carry any loads. This feature means that, especially when stretching, the pads do not play a significant role in load transfer. The simulation showed that the stress in the overlay is, on average, about half of the design stress for the cross-section of the sheet without the overlay.

The simulation did not consider the residual stresses arising after the welding of the overlays. The change in HAZ hardness was not included in the simulation.



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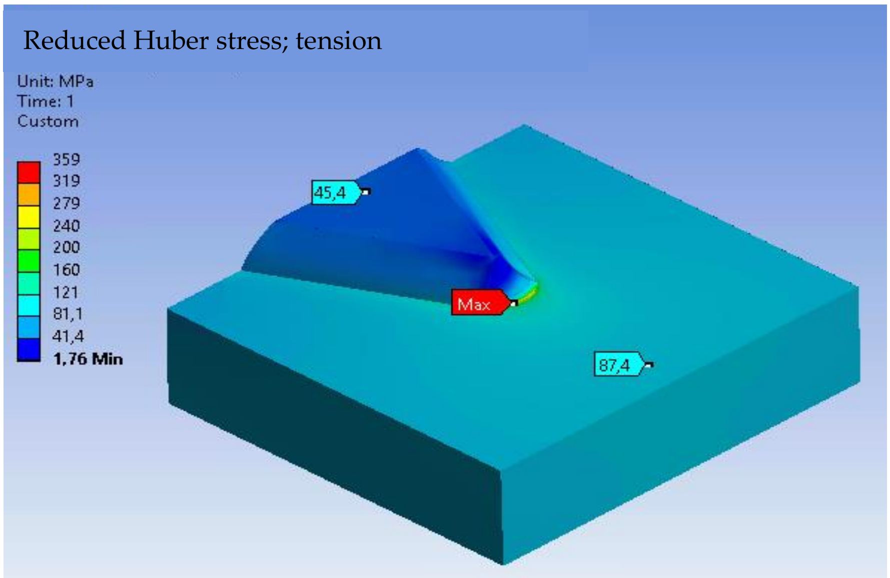

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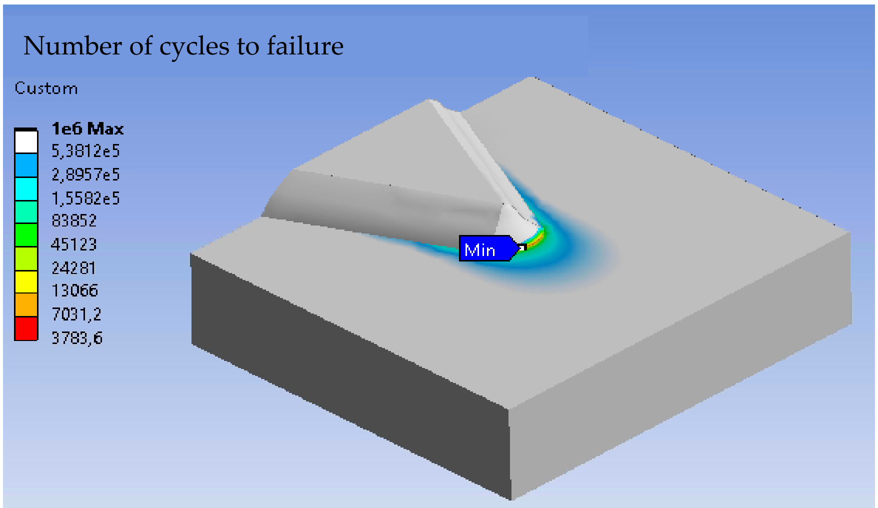
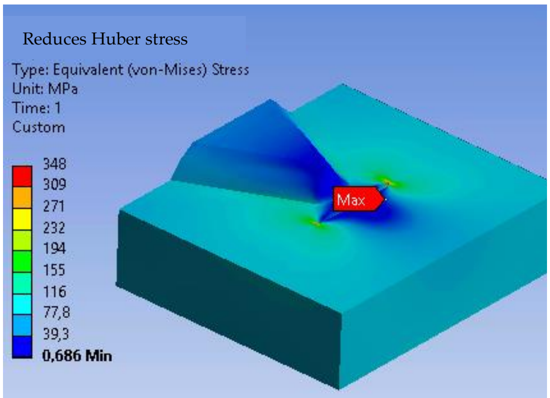


c)

Fig. 5. Huber-Mises-Henke reduced stress – tensile strength 100 kN: a) without overlay, b) with overlay c) number of cycles to failure

Figure 6 below shows the results of the main simulation (cutting out a key fragment from the entire model) of stretching a joint with a surface crack (not passing through the entire thickness of the sheet) with a length of 15 mm and a maximum depth of 5 mm. It is noteworthy that the simulation technology already allows to calculate the value of the stress intensity factor KI along the entire length of the crack line. Having the values of the material constant of fracture toughness KIC, one can attempt to precisely calculate the time to failure of any crack. For carbon steel, this parameter is about 100-200 MPa m0.5 [12-17]. Of course, the shape of this crack must be determined in advance by NDT (Non-Destructive Testing).



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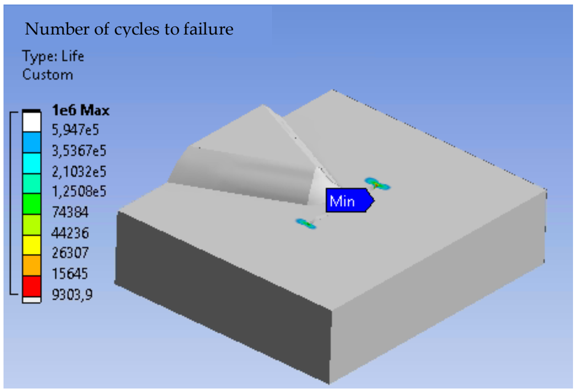

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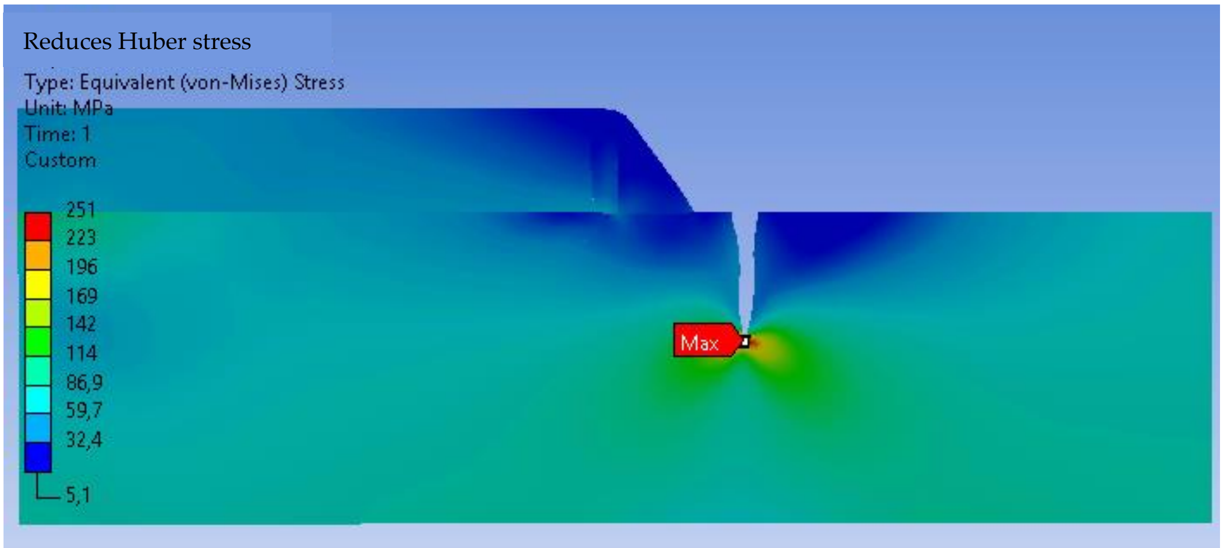

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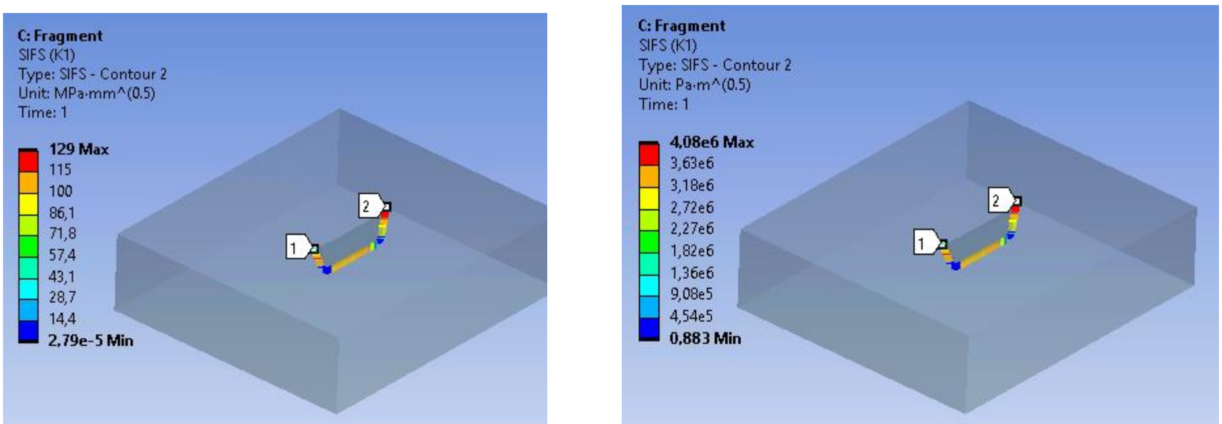

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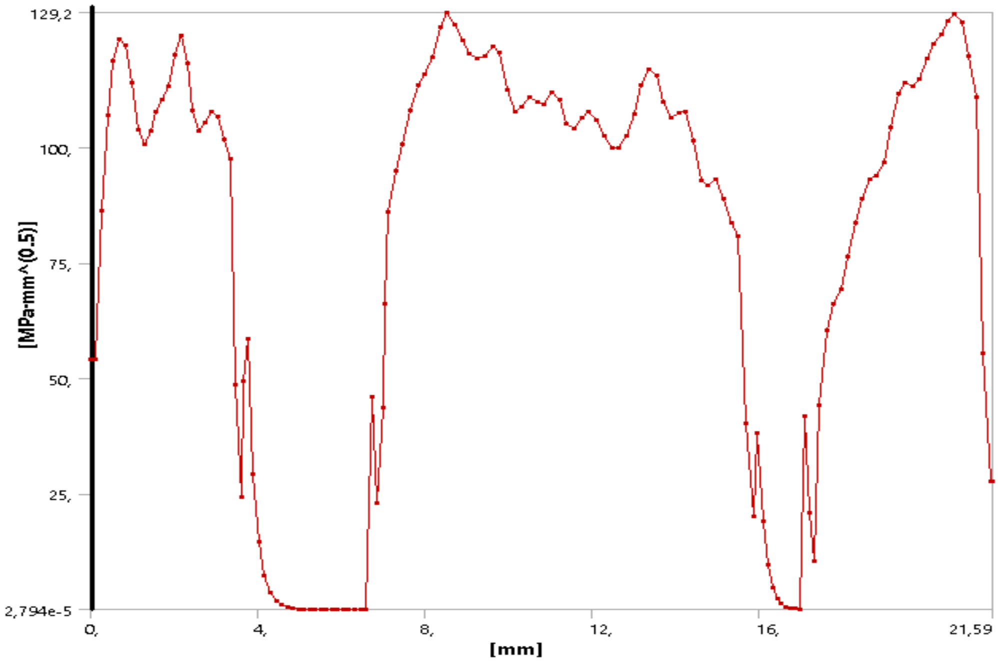

(e)

Fig. 6. Crack in front of the overlay front for 100 kN tension: a, c) Huber-Misses-Hencke reduced stress; b) number of cycles to failure; d) stress intensity factor KI along the crack edge; e) diagram of the stress intensity factor KI along the crack edge

Conclusions

1 Simulation proved that weld overlays used in plate girder structures are ballast, because they do not participate in stress transfer when tensile is dominant. In addition, they generate a stress concentration in the corner of the pad, which greatly reduces the time to fatigue failure of the structure.

2. Pure tensile loading of the joint with the cap causes a slight bending of the joint as well. This is because the centre of the cross-section does not coincide with the axis of the tensile force. This phenomenon is the main reason for the high value of the stress concentration factor SIF.

3. For bending, the value of stress concentration SIF may be even higher than for tension, but in this case its value strongly depends on the position of the overlay relative to the beginning and end of the "reinforced" flange of the plate girder.

4. Thanks to the simulation, it is possible to determine the stress intensity coefficients for any crack shape, including surface cracks, at any length.

5. The authors do not know whether the technology of precise scanning of the corrugated weld surface, the fusion line, and the conversion of the cloud of points obtained in this way into a solid model is available in the industrial sector. The lack of a perfect representation of the real surface is still a weak point of the simulation. This type of intraoral scanning is already used in prosthetics.

6. Each major project in any industry must be agreed with a fire, health, and safety and Sanitary and Epidemiological Station expert. The authors see no reason why serious welded structures should not be agreed with the engineering welding supervision. The question of which of the four EXC execution classes should be covered by such an arrangement is a secondary matter. For example, in Germany, the welded structure must be agreed at the design stage with the engineering welding supervision. We believe that good practices should be relied upon, and that cooperation and the exchange of information between construction and welding engineers are necessary.

Authors' contributions: concept, K.W.; methodology, J.N.; simulation programming, J.N.; validation, K.W., J.N.; formal analysis by K.W.; conclusions, K.W., J.N.; resources, J.N.; date curation, K.W.; text - preparation of preliminary text, J.N.; text-review, K.W.; supervision, K.W.; project administration, K.W.
Conflict of interest: The authors declare no conflict of interest.

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