KEY CHANGES IN THE WELDING OF FATIGUE LOADED STRUCTURES

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Abstract: This paper discusses welding problems of today and the possibilities for tomorrow for companies in the welding industry. By leaving old welding procedures based on traditions and applying new scientifically developed welding demands and procedures there is a vast potential to improve strength performance of the structures and increased competitiveness regarding weld work for the companies. Unfortunately, no changes are done easily and quickly and this paper gives proposals how changes can be done efficiently.

Keywords: Welding, Fatigue, Standards, Changes

1. INTRODUCTION

During the last decades, the research within welding of fatigue loaded structures has come to a point in which it really can change the way of how products could be welded according to best practice. Cross functional work between production, quality, design and product analysis gives new knowledge on how to produce and weld structures in an efficient way. Improved standards and welding procedures make it possible to increase the company competitiveness saving time and effort in the weld work. The target is to offer as long fatigue life as possible to as low cost as possible.

A main problem in industry is that many rules controlling welded structures basically were developed and specified before the introduction of computers and e.g. the extensive use of Finite Element Methods. This disagreement has been known for some decades but still most standards are missing acceptance limits for many of the most critical defects (Maddox, 2003). New methods have shown the discrepancy between the standards and the real fitness for purpose demand of the weld. Weld toe radius and weld penetration demands of fillet welds are absent and depending on how good or bad the workmanship is can the expected life of a fatigue loaded weld have a vast scatter.

The introduction of the Volvo standard 181-0004, released in 2008, is a successful outcome of research that has been performed in Sweden since the 80s. It can be seen as a pioneer work for how new welding standards should be created with scientifically based connection between defect size and expected life of the products. The new demands have given a great progress in the development of new welding procedures within operations to fulfil the critical demands. Welds are optimized to offer as long fatigue life as possible for a certain application rather than just fulfilling the standard demands.

2. ACCEPTANCE LIMITS FOR WELDS

Welding procedures and weld acceptance limits are mainly evolved from the quality that is expected from a skilled welder (Gregory, 1992). This is considered as good workmanship and the focus is on easily observed physical characteristics of the weld rather than the real effects on structural integrity. Most criteria have limited or no connection to fatigue (Marquis, et al., 2006). In a comparison of six international and national standards for welding quality criteria are demands in general based on workmanship rather than fatigue properties. One standard apply to fitness for purpose, but this standard is used for power nuclear plants and is not widespread (Shaw, 2011).

This is visual in Fig. 1. In which the expected fatigue life is shown for the different acceptance criteria for the weld classes B, C and D in ISO 5817. Many demands lack a connection to fatigue and are unnecessary demanding, like *overlap* and *excess weld metal.* Other demands are too generous like *incompletely filled groove* or *linear misalignment* and can ruin the fatigue life if they are present. In an ideal standard there should be a clear and consistent connection, assuring that a certain welding class always implies to a certain fatigue life of the welded joint (Karlsson & Lenander, 2005). At the current state, the designers have no other choice than to assume average fatigue strength due to missing guidelines for high quality in production and absent instructions for taking advantage of the high quality welds in the design (Marquis, 2010).

The author of the International Institute of Welding, IIW, *Recommendations for fatigue design of welded joints and components* have done the following statement regarding ISO 5817: *"This standard has a congenital defect. It is an adoption of the old German standard DIN 8563, which was established as a standard for communication between the welders and the inspectors. The classification criterion was the difficulty, the expenses or the efforts to fabricate or to inspect by NDT. It was not fatigue strength. So by the nature, ISO 5817 cannot be applied directly to fatigue problems; it is un-scientific and inconsistent in respect to fatigue properties and needs application guidance."* (Hobbacher, 2009)

The most important geometrical parameters of the welds are the notch radius in the weld toe and depth of penetration in the root (Samuelsson, et al., 2008). This is shown in Fig. 2. The discrepancy between the demands and the structural integrity may give rise to problems and unnecessary cost also in the weld shop. Typically the weld demands are similar for all load conditions, meaning that same welding procedures are used. These results gives a miss-directed focus were the welder not consider the critical characteristics of the weld before any other demand. All demands are getting the same attention, according to good workmanship, while most of them do not add any value for the customer regarding structural integrity. In worst case, there are fulfilments of non-critical demands done on behalf of the critical characteristic (Åstrand, 2013). Studies actually show a contradiction between large throat size and large weld penetration, meaning that it can be beneficial to specify and aim for a lower throat size and receive an enhanced penetration and by that an improved fatigue strength (Drosos & Kotsakis, 2014).

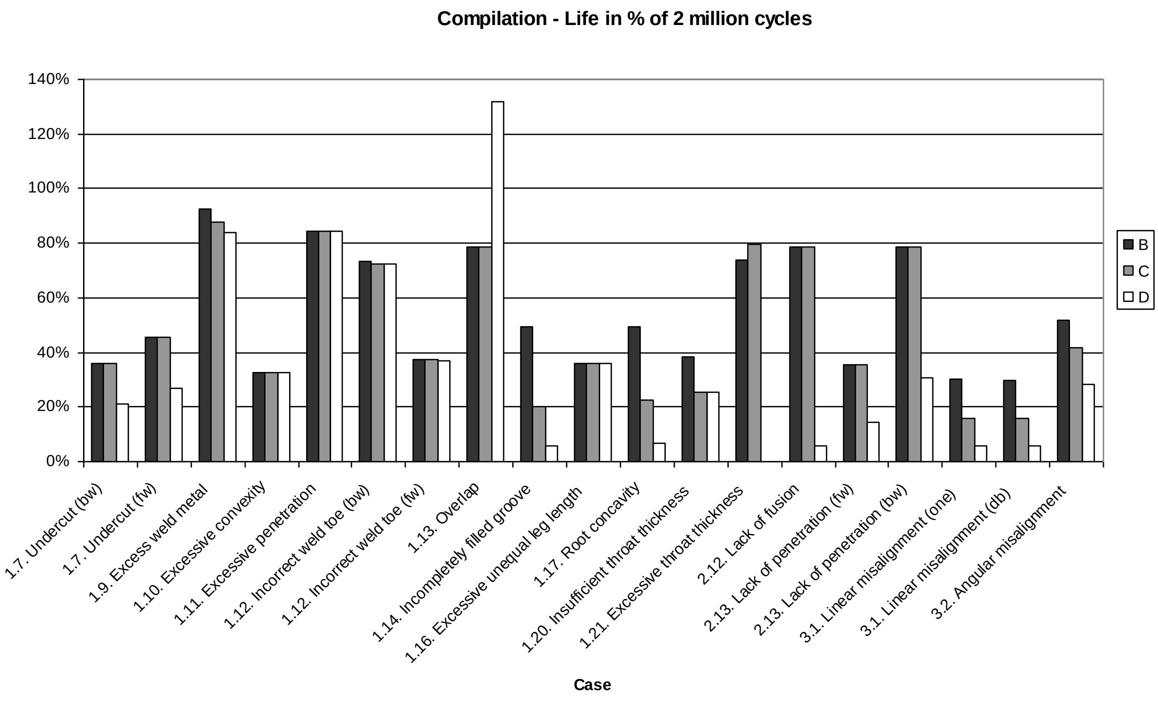

Fig. 1. Expected life according to ISO 5817 and the different weld classes (Karlsson & Lenander, 2005).

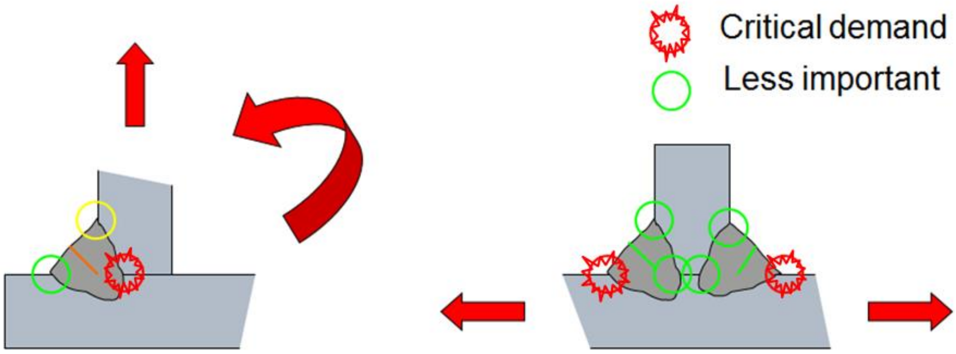

Fig. 2. Critical and less critical characteristics of fillet welds with a load carrying weld to the left and a non-loading carrying weld to the right (Åstrand, 2013).

In a study of 122 cross sections of fillet welds were the theoretical fatigue strength evaluated. The result point out that welds with leg deviation offers better and more predictable fatigue strength from the same welding parameters, compared to the traditional throat size demands. The contradiction was then that many of the best samples, from fatigue point of view, not were accepted by the throat size demand due to low throat size or too large leg deviation (Åstrand, 2012).

During welding there is a large variation due to deviations in the incoming materials, between welders and in the process itself. The penetration and radius varies and also the throat size varies. There is also a contribution in the variation from the measuring process, which can be equal to the variation from the process. A consequence of this is that the actual target value of a throat size of 5 mm with lower specification limit 4.5 mm will be 6 mm. (Hammersberg & Olsson , 2010) This has been confirmed in studies were an over-welding of around 40% has been observed (Ericson Öberg, et al., 2012).

Due to the variation and absence of critical demands a weld with a given demand can look completely different as shown in Fig.3. The two welds are both accepted by ISO 5817 weld class C with throat size 5 mm and correspond to worst and best case from the large scatter of welding. The weld *A* has no penetration, a minimum size and sharp transitions between the weld and base material. The weld *B* has large penetration and an oversized weld with smooth transitions. Due to lower stress and stress concentrations for *B* the fatigue life can varies up to 6 times for a real application (Widehammar, 2014). The cause for this is that the most critical characteristics weld penetration and weld toe radius do not have any acceptance limits. Designers then have a delicate situation in which they know what is critical and what needs to be controlled but don't have any tools to secure the fulfilment after welding. The situation is even more complicated if fatigue testing is used as a verification of the design. There can be good quality for the tested sample but in reality can a much lower quality be received without any reasons for rejection. If the critical part of a structure, for example, need to last minimum 2 million load cycles. During testing it lasted 3 million cycles. It is then easy to believe that it was a good design and welding procedure, but if this was a good sample like in Fig 3 B and we then receive a quality like Fig 3 A can the real fatigue life be far under 1 million cycles.

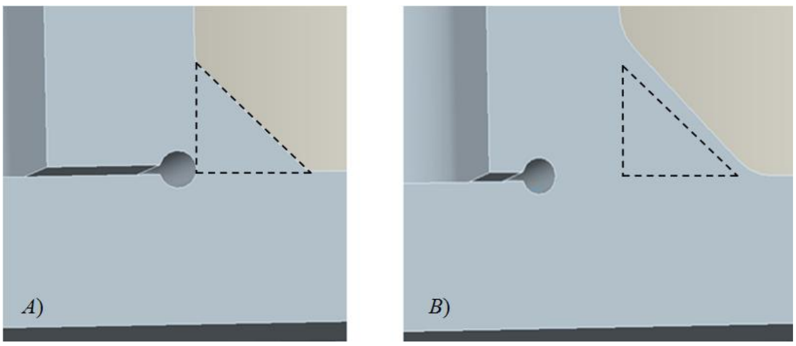

Fig. 3. Accepted welds according to the same design criteria in ISO 5817 with throat size 5 and weld class C. The dotted triangle is equal to throat size 4.2 mm.

3. FUTURE STATE OF WELDING

The potential for improvements in fatigue life is vast and outside the traditions and standards of today. If the boundary of how a weld should look like is absent and the focus is on the critical characteristic new possibilities are exposed. To get the real effect it is necessary to connect the design of the welding procedures and the welding demands. The focus should be on the critical demands and the key is to use the best practice in both design and in production. In IIW "design for purpose" is on the agenda, which relates to the possibility of the weld to perform its required function during the life of the structure. It also means that the designer must be able to distinguish the primary function of the joint and put demands based on the function, like the examples in Fig. 2. (Marquis, et al., 2006). Recently the term "weld for purpose" has been highlighted, meaning that the welding procedures are adapted to the function of the weld and prioritise the part of the weld that create value to the structure which most often is to enhance the strength.

Volvo Construction Equipment, VCE, is one of the pioneers within this area with their welding standard for life-optimized welded structures, 181-0004; it is a result of a continuous work in different research projects since the 80s. The development has been necessary in order to produce new generations of machines which should be able to load more, drive faster and last longer. The total numbers of load cycles are increasing as well as the number of functions. This means that new technology has to be used to avoid increased weight and fuel consumption (Samuelsson, 2010).

Based on the experiences from VCE the work can be divided into the following step to reach the perfect stage in the development of design and weld for purpose:

1. *Connect the weld demands to fatigue life*: This has to be done to create an understanding for fatigue in the organisation and to learn how different factors affect the structural integrity. The key is to include the fatigue critical demands weld toe radius and the weld penetration in fillet welds as shown in Fig. 4.
2. *Develop welding procedures that offer as long fatigue life as possible*: When the knowledge of the important characteristics for fatigue are at a high level it is time to start optimizing the welding procedures for different joints. Typically it is about prioritise and optimise the weld toe radius and/or the penetration. A major challenge is to allow "lower" quality at other parts of the weld which does not affect the structural integrity.
3. *Update weld demands and welding procedures*: Merge the knowledge of fatigue critical points with the optimised procedures for fatigue and create weld demands that support new welding procedures. The situation that arises during the development of welding procedures for fatigue is that the welds with the best fatigue life properties deviate from the traditional demands and will be seen as defects. This step is then done to support welds with excellent fatigue properties and to make them preferred according both fatigue life and weld demands.

Without passing all these steps it is impossible to take full advantage. Step 1 gives the designer a tool for a predictable fatigue life of the structure. Which of cause is essential, but the real improvement is done in the following steps with new welding procedures that also can enhance the performance of the weld. New welding procedures supported by adopted demands can contribute to both reduced cost and to double fatigue life. Fig. 5 illustrates how the development has to be done simultaneously connecting both the theories of fatigue cracking and the physics of the welding process to create welding standard were it is easy to produce weld with excellent fatigue properties in a cost effective way.

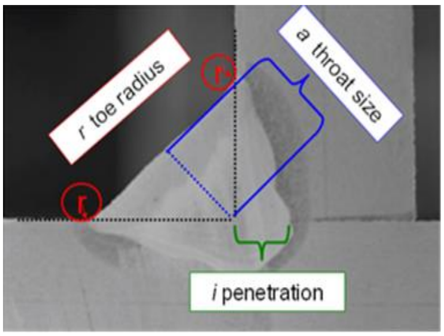

Fig. 4. A fillet weld with the new Volvo standard demands: toe radius and the weld penetration, *i*, together with the classical throat size demand, *a*.

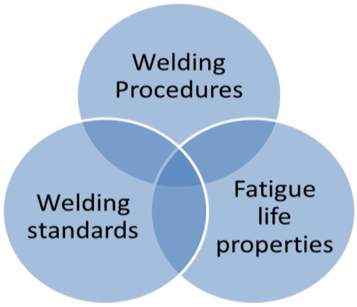

Fig. 5. To reach an ideal situation for welding of fatigue loaded structures must the standard consider both welding procedures and fatigue life properties.

VCE took the first step in 2008 with the development of the welding standard 181-0004. In the project WIQ, Weight reduction by Improved weld Quality (supported by The Swedish Governmental Agency for Innovation Systems, VINNOVA) the development of welding procedures was done, showing both limitations in the demands and the need to reduce some demands to get excellent quality in another critical point.

In 2013 the standard was updated, including a new weld class, VE. The class is used when the root is critical and it has as a consequence lower demands on the surface, making it possible for the welder to prioritize the root. There is however need for further updates, since some of the best welds from fatigue point of view are still not accepted by neither the standard or the typical welder. It can in fact be best practice to weld with the traditional defect types like undercuts and leg deviations (non-symmetric) for many applications to create a large radius or a deep penetration. Figure 6 shows two examples of how welds can look like making it possible to improve the properties in the critical spot of the weld in comparison to Fig. 2.

4. BENEFITS

A state were the designer put demands that actually are relevant for the structure means several benefits. The total amount of weld metal can be reduced by adopting such demands. In general this is about increasing the demands for the critical 5% of the welds and reducing the demands for the non-critical 80%. Then, focus is on the critical spots with improved properties and reduced cost for the non-critical ones. In a study of a component with global demands the metal weight could hence be decreased with 28% together with reduced weld class demands without reducing the integrity of the structure (Stemp, 2012).

By applying an improved quality at critical points in the new design the structures can either load more, last longer or be lighter. If an improved procedure can be applied at the critical point of the structure it is fully realistic to load 25% more without adding any cost or weight to the structure (Åstrand, 2013). Reduced weight and possibilities to utilise high strength steels are related benefits depending on the need of the structure. Some of the potentials are available today but there is often a high resistance to introduce post weld treatment operations like TIG-treatment or grinding in the weld shops. It is then easier and more cost efficient to introduce improvements with the existing welding process.

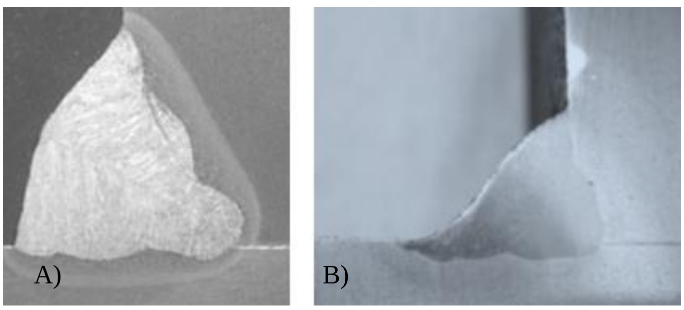

Fig. 6. Welds performed for improved fatigue properties in the weld root, A) and in the lower weld toe, B) (Åstrand, 2013).

Increased knowledge about the welding process and the demands can also be used to reduce the fabrication cost. In an improvement project within Volvo CE, dealing with a real welded component the weld class could be reduced to VE for a large amount of welds showing the importance of the penetration. At the same time the weld throat size could be reduced. By applying a “weld for purpose” approach in the robot programs it was possible to: weld more, increase the penetration, weld faster and increase the arc on factor. This gave an enhanced fatigue life of the structure and made it at the same time possible to produce 14% more in the same equipment.

5. SUMMARY

The current guidelines and standards make it difficult to utilise high quality welds in the design of fatigue loaded structures because they are based upon traditions rather than fatigue life properties considerations. Hence there is a great potential to make structures better, lighter and cheaper with a changed approach. To reach an improved state is it necessary to co-operate between departments and apply a design and weld for purpose approach were the focus is on the critical spots of the structure and on the weld itself. This is however not done in a rush and requires a commitment from the company and several years of hard work and research. Volvo CE has now come quite far on this road with acceptance limits in the welding standard which actually connect to fatigue life. Volvo CE has also explored the potential of a doubled fatigue life with optimised procedures based on the critical demands and the possibilities to make structures both better and cheaper.

The welding process is often seen as mature but in reality this is not the case. It may be mature at its current state and even trapped into its own traditions and regulations. This relate to the fact that no real change has been done internationally during the last decades even if it is known that the current way of working not is the best. Volvo CE has however taken the opportunity to develop and apply the best knowledge thanks to a continuous research and usage of an own standard. The research performed can be seen as a good example of how to go from research to new standards and performed improvements in both design and fabrication, making it possible to produce structures with improved and predictable quality in a cost effective way. Changes are not done by themselves and it is a slow process since it requires a new way of working for all people involved in the design and fabrication of welded structures. The potential in reduced weight and cost makes it however worth the efforts.

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