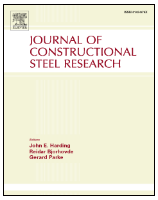
Journal of Constructional Steel Research 139 (2017) 374–384

Contents lists available at ScienceDirect

Journal of Constructional Steel Research



Fatigue strength of repaired cracks in base material of high strength steels

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ARTICLE INFO

Article history:
Received 6 October 2016
Received in revised form 27 September 2017
Accepted 4 October 2017
Available online xxxx

Keywords:
Very high strength steels
Repair weld
Base material
Artificial crack
Fatigue

ABSTRACT

Fatigue crack formation is an inevitable issue for welded steel structures subjected to cyclic loading. Accordingly, repair of the fatigue crack in welded steel structures is unavoidable to prolong fatigue life. However, there is limited knowledge available about the procedure to be adopted for the repair and the life extension to be expected after the repair. The current paper is focused on the effects of the repaired an artificial crack in the base material of S690 and S890 high strength rolled steels on the fatigue strength of the material. An artificial crack was created in the middle of the plate test specimens by spark machining and subsequently, the crack was repaired by using the FCAW (flux-cored arc welding) process. The repaired specimens were tested in a four point bending test rig with a constant amplitude loading for creating a uniform bending moment at the weld region such that the weld cap to be exposed to tensile stresses. The test results show that most of the fatigue cracks initiated at the start-stop points of the weld cap and the fatigue crack initiation life of the specimens occupy approximately 45% of the total fatigue life. The statistical analysis of the test results revealed that the characteristic fatigue strength of the repaired specimens is very close to the detail category 160 of EN 1993-1-9 [5].

1. Introduction

Modern steel manufacturing techniques make it possible to produce very high strength steels for various application purposes. The application of very high strength steels has enormously increased in the automotive industry in the course of the last decades. Although very high strength steels with good weldability, toughness and yield strength up to 1300 MPa are available for structural application purposes, the use of very high strength steels in the civil engineering structures is rather limited due to lack of knowledge about consequences of manufacturing process and limited available experimental evidence of the structural behaviour of the material.

The use of very high strength steels results in slender members with reduced wall thicknesses which lead to low self-weight and volume of structures. This results in cost savings in production, transportation and erection. In case of welded connections, the slender member with thin wall thicknesses will allow for the smaller weld volumes hence, decrease in weld consumables and lower energy consumption to make the welded connections. Nevertheless, low self-weight of very high strength steel structure causes a high stress variation under live load. Consequently, the fatigue strength of very high strength steel structures is one of the main design criteria for the effective application.

Gurney [1] determined that the fatigue strength of the material becomes more sensitive to the entity of notches and to the surface condition with the enhancement of the material yield strength. In accordance with this, the fatigue sensitivity can be reduced with the reduction of stress concentrations. With the disregarding surface condition of the material, the fatigue strength increases with the higher yield strength of the material. Maddox [2] concluded that the fatigue strength of welded connections is independent of the material yield strength. This was based on the assumption that the welding application leads to micro-cracks which are likely to give rise to fatigue cracks. Accordingly, the fatigue crack propagation life is determinant for the fatigue life of welded connections and depends on the stress ranges, being independent of yield strength. The determination of the fatigue strength of the base material and welded connections made of very high strength steels has become one of the main research topics in the last decade. Demofonti et al. [3] performed fatigue tests on the butt welded specimens with 10 mm thickness and made of S355 up to S960. The results showed that no significant fatigue strength difference exists under constant amplitude loading condition while the beneficial effects of S960 steel investigated under variable amplitude loading condition. In addition, the advantage of very high strength steels on the fatigue strength was determined with reduction of the notch factor which was achieved by machining of the welds. In the framework of a research program of ECSC, Puthli et al. [4] carried out fatigue tests on various butt welded specimens with a thickness of 6–8 mm made of S690, S960 and S1100. The characteristic fatigue strength for all steel

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https://doi.org/10.1016/j.jcsr.2017.10.005

Table 1
Chemical compositions of test materials [%wt].

Grade	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %
S690	0.16	0.19	0.87	0.012	0.002	0.33	0.22	0.06
S890	0.168	0.281	0.98	0.012	0.0008	0.494	0.511	0.98
Grade	V %	Nb %	Al %	Cu %	N %	B %		
S690		0.026	0.085		0.0038	0.002		
S890	0.041	0.011	0.074	0.024		0.0022		

Table 2
Mechanical properties of test materials.

Grade	$R_{p,0.2}$	R_m	A5	KVC	
				−40 °C	−20 °C
	[MPa]	[MPa]	%	[J]	[J]
S690	800	830	17		251
S890	985	1051	14.3	36	

grades was found to be above of the recommended design values of EN 1993-1-9 [5]. The test results of the specimens made of S1100 showed the tendency for the decrease of the free slope to $m = -5$. Pijpers et al. [6] concluded from the fatigue tests on the base material and transverse butt welded specimens made of S690 and S1100 that the fatigue crack initiation life of very high strength steels is longer than mild strength steels. Kuhlmann et al. [7] showed that the post weld impact treatments are very effective for improving the fatigue strength of welded connections made of very high strength steels. The effectiveness of post weld impact treatments on fatigue strength of very high strength steels is already standardised in IIW recommendations [8]. Berg et al. [17] concluded that the fatigue strength of high frequency hammer peening treated welded connections made of S960, S1100 and S1300 is at least twice the fatigue strength of the as-welded condition.

As concluded by Gurney [1] and Pijpers [9], the fatigue strength of very high strength steels is susceptible to the surface conditions and the presence of notches. Therefore, the base material with high surface roughness might cause the fatigue crack initiation in the structural elements or even in the base material of welded connections made of very high strength steels. Once the cracks are detected the repair of the base material becomes essential for fatigue life extension.

Yamasaki, et al. [10] focused on the effects of the repair weld on the fatigue crack growth behaviour in the base material of JIS SM50A steel plates with the yield strength of 323 MPa. Fatigue cracks with certain length were created in the pre-notched specimens. The created fatigue cracks were repaired by X-shape welding under three conditions: with applying an axial tensile stress, without external stress and open cracks condition to induce compressive stress with releasing open state after the repair. The results showed that the fatigue crack growth rate in the repaired specimens is higher than the growth rate in the base material and the artificially induced compressive stresses improved the crack growth behaviour of the repaired specimens. Kudryavtsev et al. [11] investigated the effectiveness of various repairs and retrofit methods for the fatigue cracks in the base material of low alloyed steel with the yield strength of 367 MPa. The hole drilled plate test specimens were subjected to fatigue load to create fatigue cracks at the edge of the hole. The crack propagation was permitted until certain size and the fatigue crack were repaired/retrofitted by the following techniques: drilling a hole at the crack tips with and without cold working, drilling a hole at the crack tips with installation of high strength bolts, overloading of the section, local explosive treatment, local heat treatment, repair by welding with and without ultrasonic peening of the weld toes. The repair by welding with ultrasonic peening provided the longest fatigue life after the repair. According to the test results, the repair by welding without ultrasonic peening was the second effective method for the fatigue cracks repair.

The state of art shows that the fatigue strength of the base material improves with the increase of the yield strength of the material. Nevertheless, the surface conditions can influence of the fatigue strength of the material and lead to fatigue crack initiation in the base material. For fatigue life extension, the repair of the base material cracks becomes essential. However, limited knowledge is available for the fatigue cracks repair procedure, consequences of the repair on the base material of very high strength steels and possible fatigue life extension after the repair of the cracks. This paper presents the repair process of artificially created cracks in the base material of S690 and S890 rolled steels and the fatigue test results of the repaired specimens.

2. Plate material properties

Table 1 gives the chemical compositions and Table 2 the mechanical properties of the test materials. The values of the mechanical properties and the chemical compositions are taken from the material certificates.

3. Test specimens

The test specimens were cut from S690 and S890 plates by water cutting and have a length of 990 mm and a width of 160 mm. In the middle, the width of the specimens was reduced to 150 mm (see Fig. 1).

For performing the repair procedure, a crack is artificially created in the middle of the specimens. The predefined crack shape and crack size ensure a controllable material removal process and a repair weld with similar length and depth in all specimens. Consequently, this allows the appropriate evaluation for the test results straightforward without the influences of variation due to manufacturing process. The artificial cracks were created by electrical discharge machining (EDM) process.

In practice, the fitness for purposes analysis is carried out to determine the time period for fatigue crack propagation from the detected crack size to the allowable critical crack size. Accordingly, the inspection and repair intervals are specified based on this time period. For simplification of the analysis, half the thickness of the section is assumed to be the allowable critical crack depth unless any other restrictions are defined. With the same approach, the depth of the artificial crack is

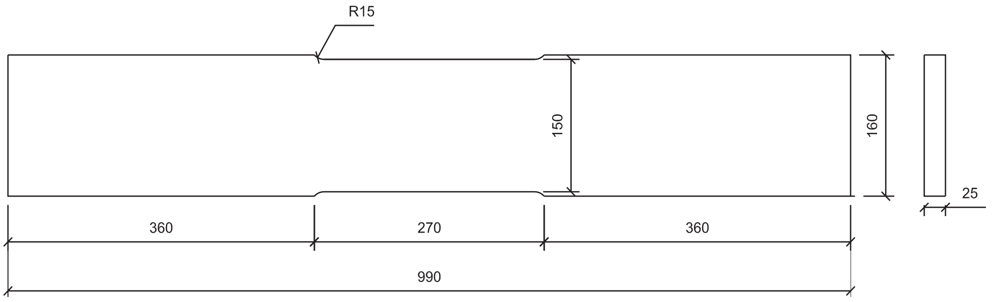

Fig. 1. Dimensions of the test specimens.