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Structural Integrity Evaluation of the "Constitución de 1812 bridge", over the Cádiz bay (Cádiz, Spain)

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Abstract

As required by the latest regulations, an inspection and maintenance plan has been drafted for "Constitución de 1812 bridge over the Cádiz bay" (Cadiz), which defines the tasks to be performed in the different elements of the bridge during its service life. The part of the plan related to the inspection of the steel structure has a section dedicated to the inspection of defects or notches that can be produced in the steel deck, providing critical defect sizes above which the safety of the structure would be compromised. With this purpose, in the most stressed points of the deck, the construction details which are more susceptible to fatigue have been identified. Fatigue tests of these details have been performed to complete a structural integrity assessment which also comprises the determination of the material fracture toughness and the definition of critical crack sizes. The tests were carried out on specimens obtained with the same steel grades used in the bridge and with the same welding procedures practiced in the structure. The results show that typical critical crack sizes are around 12 mm, with structural details having critical crack sizes around 6 mm.

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Keywords: : Inspection, fatigue, fracture, steel deck.

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1. Introduction

Following the latest revisions of standards such as EHE-08 [1], EAE [2] or IAP11 [3], more and more resources are being allocated in the design and construction phase, to the preparation of inspection and maintenance manuals that cover the complete life cycle of the infrastructure. These manuals define the tasks to be performed in the different elements of the infrastructure and the periodicity of these tasks until the end of the corresponding service life.

Requested by the "Ministerio de Fomento" of Spain, these documents have been prepared for the "Constitución de 1812 bridge" over the Cádiz bay (Cádiz, Spain) [4]. In this case, as part of the inspection of the metallic structure, a structural integrity approach has been completed. This approach is explained below.

2. Basic description of the bridge

The Bridge of the Constitution of 1812 on the Bay of Cadiz [4], see figure 1, gives access to the city of Cadiz from the end of Puerto Real, giving rise to the third access to the city along with the isthmus to San Fernando and The Carranza Bridge.

Fig. 1. Bridge of the Constitution of 1812.

It has a total length of 3,157 m with a cross section of 32.5 m wide formed by three sidewalks separated by medians. Two of the roadways, with two lanes each, are intended for light and heavy traffic and the other road now serves as a bus lane which, in the future will host the tram that will link Cadiz with Puerto Real, see figure 2.

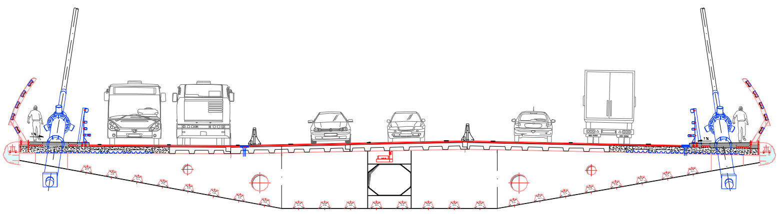

Fig. 2. Section of the deck of the cable-stayed section.

3. Theoretical study

The information included in this article focuses on the cable-stayed viaduct of the bridge of the Constitution of 1812.

This viaduct was built by balanced cantilever, so in addition to the welded joints in the workshop of each of the sections, there are numerous welded joints executed on site.

The work has begun with the identification of the most stressed areas and therefore more prone to suffer phenomena of fatigue. In these areas, the existing welding joints have been analyzed by determining how they sustain the loads and the corresponding stresses, which has allowed to elaborate a manual with the most critical welds of these zones.

Taking into account the existing welding joints, four coupons representing the main welded joints have been made and mechanical tests have been performed in order to complete a structural integrity study of the actual joints, with the aim of determining the corresponding fracture toughness of the material and the critical crack size.

The tests were carried out on specimens obtained with the same materials (steel grades) used in the bridge and with the same welding procedures practiced in the structure.

4. Identification of the most stressed areas of the deck

Several finite elements models have been developed on which the restrictions and actions defined in the bridge project have been applied. In this way the most stressed areas of the deck have been determined.

Throughout the document, mention is made of the different sheets composing the metallic deck. In order to be able to easily identify each one of the plates, they have been given the numeration shown in the diagram gathered in figure 3.

Fig. 3. Identification of the different plates composing the bridge deck.

In the different zones of the deck there has been a selection of the welded joints that, because or their geometry, may be prone to cracking processes. Moreover, considering how the different zones of the deck work, the main stresses in the metallic structure can appear in both the longitudinal and the transverse directions of the bridge. Therefore, welded joints in both directions have been analyzed.

5. Test coupons

Considering those joints identified as being more susceptible to fatigue phenomena, four different types of joints have been defined. These types are considered to be representative of the welded joints of the bridge. Moreover, test coupons of the four different types of joints were fabricated, ensuring that the welding conditions are fully representative of those developed on site. The joints executed are described below.

The first joint is a butt weld executed following the manual procedure 136-FCAW according to UNE-EN ISO 4063 [6], see figure 4.

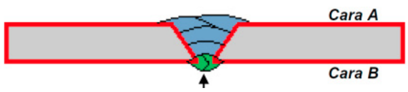

Fig. 4. First type of welded joint.

The second welded joint obeys to the requirements of the weld execution found in site. In some cases the gap between the plates being welded is larger than that one strictly necessary to complete the welding process. In such cases, weld beads where firstly applied on the edges of the plates being joined and, secondly, once the weld root was executed, the whole weld was completed, see figure 5.

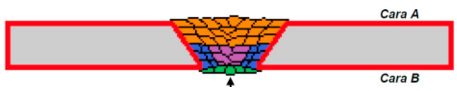

Fig. 5. Second type of welded joint.

The third joint is made between a 25 mm thick plate and a 40 mm thick plate with a transition slope of 5/1, see figure 6.

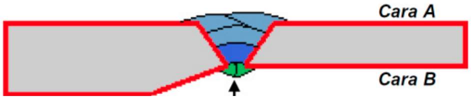

Fig. 6. Third type of welded joint.

The fourth joint being analyzed is a T-welded joint, with plate thicknesses of 25 mm and 20 mm, see figure 7.

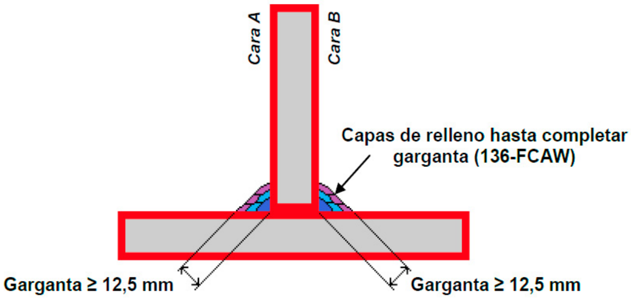

Fig. 7. Fourth type of welded joint.

From the above mentioned coupons (types of joints), specimens were machined to complete tensile, fracture and fatigue tests, hardness measurements and microstructural analysis.

6. Tensile Tests

The study of structural integrity of welded joints begins with the determination of the tensile properties of the base material, the weld and the thermally affected zone. From each of the test specimens, tensile tests were carried out to compare them with the minimum requirements associated with S-355J2 + N [7] steel, which guarantees a minimum yield strength of 355 MPa, a minimum ultimate tensile strength of 470 MPa (for plates with a thickness 3 <t <100mm) and a minimum elongation at failure of 22%.

A total of 18 tensile tests have been carried out, 3 in each of the 6 areas of interest: base material, weld and thermally affected area, all in longitudinal and transverse directions to the weld joint. The tests were carried out according to the standard UNE EN ISO 6892-1 [8].

After analyzing the obtained data, it was possible to verify that the test specimens of base material meet all the specifications (elastic limit and strain and deformation at break) corresponding to S-355J2 + N steel.

The tests on the weld specimens exceed the minimum ultimate tensile strength specified for S-355J2 + N steels with a large safety margin, while the strain at maximum load were lower than that specified for the base material.

The specimens in the heat-affected zone, in the same way as the specimens tested in the weld, exceed the minimum ultimate tensile strength specified for the base material S-355, while the required minimum deformation falls below the specification.

7. Fatigue characterization

The fatigue behavior of the weld joints has been determined by two ways, the theoretical (normative) and the experimental. In the experimental analysis the fatigue tests were carried out on test pieces obtained with the same materials (steel grades) used in the bridge and according to the same welding procedures practiced in the structure. Therefore the fatigue behavior of the weld joints executed in site is analyzed and its similarity with the values proposed by the normative is verified.

According to EC3 [5] the detail category corresponds to class FAT 71 for the weld joints manufactured.

The experimental program was performed by obtaining the experimental S-N curves by testing 48 specimens corresponding to the four types of exposed weld joints (in T, butt, with regrowth and with different thickness). From each type of joint, 12 specimens with at least 6 different load levels have been tested. The tests have been carried out following the specifications of ASTM-E466-07 [9].

The results obtained show that the FAT class for joint types 1, 2, 3 and 4 are respectively 68.77, 85.18, 79.69 and 75.57. Figure 8 shows the graph with the fatigue results of the T-joint specimens.

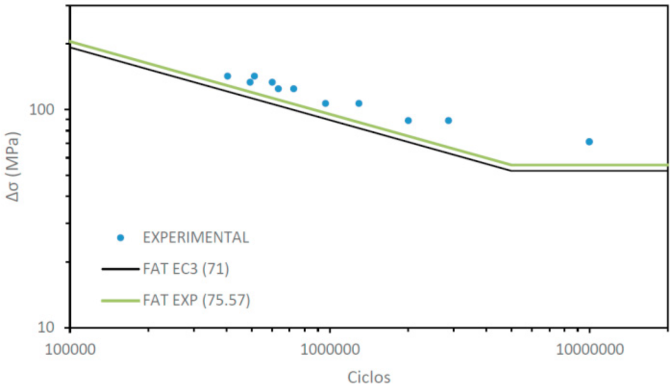

Fig. 8. Results for T-joints.

- The failure of the test pieces is located above the S-N curve indicated by the EC3 [5] (FAT 71) for the four geometries being analyzed.
- Butt joints have a higher dispersion, resulting in an experimental FAT class slightly lower than that proposed by the EC3 [5]. In any case, the experimental results are all above the EC3 curve.
- The rest of the joints tested have fulfilled the FAT class required by the EC3 [5].
- The results obtained contribute to ensure the validity of the execution on site, and in any case they demonstrate the suitability of using the EC3 fatigue curves for the joints being analyzed.

8. Determination of microstructure and hardness

In order to analyze the microstructure of all welded joints, samples have been prepared by polishing and etching with Nital to reveal the different regions in the welding area (base metal, thermally affected area and weld). In addition, the Vickers hardness of the weld has been determined using a micro-indentator.

After having carried out all the tests and analyzing the results obtained from them, the conclusions obtained are:

- The hardness of the base material, ZAT and weld at all joints (T, butt, with regrowth and with different thickness), is adequate according to the material composing the specimens (maximum values of 189 HV in base material, 304 HV In ZAT and 274 HV in the weld).
- The observed microstructures correspond to the structural steel being analyzed. Ferritic-perlite microstructure in base metal, acicular ferrite, perlite, bainite and martensite in the ZAT and acicular ferrite corresponding to the filler material.

9. Characterization of fracture properties

The fracture toughness of the material was determined by J tests of CT specimens extracted from the base material, the weld and the thermally affected area, using the parameter K_J (hereinafter Kmat) as a characteristic fracture parameter. For the execution of the J tests, the indications of the ASTM E1820-13 [10] have been followed.

A total of 18 tests were carried out, 3 in each of the 6 areas of interest: base material, weld and thermally affected area, all in longitudinal and transverse directions to the joint.

The CT specimens are prefixed with the load specified in the standard until the crack length is:

$$0.45 \cdot W \leq a_0 \leq 0.7 \cdot W \tag{1}$$

Where:
W is the width of the specimen
a_0 is the crack length

Taking into account that the fracture resistance of a material decreases when decreases the temperature and in order to ensure a minimum tenacity independent of the weather conditions to which the Bridge of the Constitution of 1812 is subjected on The Bay of Cadiz, the test campaign has been carried out at -20 ºC (clearly very conservative conditions).

The fracture toughness of the material has been determined from the following expressions:

$$J = J_{el} + J_{pl} \tag{2}$$

$$J_{el} = \frac{K_I^2 \left(1 - \upsilon^2\right)}{E} \tag{3}$$

$$J_{pl} = \frac{\eta \cdot A_{pl}}{B_N b_0} \tag{4}$$

Where:
J is the integral J
J_{el} is the elastic part of J
J_{pl} is the plastic part of J
K_I is the stress intensity factor
ν is the Poisson ratio
E is the modulus of elasticity
η is $2 + 0.522b_0 / W$
A_{pl} is the area of the plastic zone
B_N is the net thickness of the specimen
b_0 is the initial remnant ligament (W-a)

As main conclusions can be said that:

- For the test, very conservative working conditions (-20ºC) have been considered, obtaining fracture resistance values on the safety side.
- The fracture strength value of the material is high, K_{mat} = 125.99 (MPa.m0.5).

10. Characterization of structural integrity of welded unions

The characterization of the structural integrity of the welded joints present in the Bridge of the Constitution of 1812 has been carried out by determining the crack size that compromises the safety of the structure. For this purpose, the mechanical properties of the materials, the geometry of the joints and the stress state of the joints have been considered, with maximum tensile nominal tensions (ELU).

Structural integrity assessments have been made using the Failure Diagram defined under option 1 proposed by the British Standard 7910 [11]: L_r versus K_r, see Figure 9, where only the tensile properties of the Material (yield strength and tensile strength) are required.

$$K_r = \frac{K_I}{K_{mat}} \tag{5}$$

$$L_r = \frac{\sigma_{ref}}{\sigma_y} \tag{6}$$

Where:
K_r represents the situation against fracture
L_r represents the situation against plastic collapse
K_I is the stress intensity factor
K_{mat} is the fracture resistance of the material
σ_{ref} is the reference stress
σ_y is the yield stress of the material

In the study, three different types of cracks have been assumed: through thickness crack, semielliptical crack with aspect ratio of 0.1, and semielliptical crack with aspect ratio of 0.5. The initiation of fracture has been analyzed (no ductile tearing considered) [11] and the mismatch effect [11] has not been taken into account, hypotheses that provide an additional safety margin against the final failure.

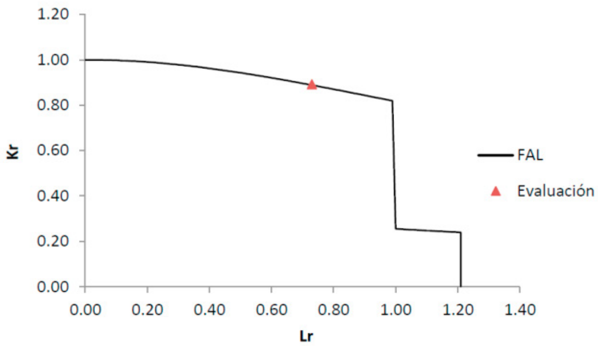

Fig. 9. Evaluation of structural integrity using the Failure Diagram.

The reference stress is obtained from the compendium of solutions proposed by BS 7910 [11], for which it is necessary to know the nominal stress acting on the structure being analyzed (primary stress of mechanical origin). The secondary stresses (residual stresses caused by the welding process) do not affect the reference stress. The definition of the stress intensity factor requires taking into account both the mechanical stresses acting on the structure (primary) and residual (secondary) stresses caused by the welding process. The residual stresses proposed by BS 7910 [11] vary depending on the type of welded joint being analyzed. In addition, the self-balancing component of the residual stress profile (K_{sb}) must be taken into account. In all cases the welded joints being analyzed are assumed to work as infinite plates.

$$K_I = \left[(Y\sigma)_p + (Y\sigma)_s\right] \cdot \sqrt{\pi a} + K_{sb} \tag{7}$$

Where:
KI is the stress intensity factor
(Y σ) p is the primary stress intensity correction function
(Y σ) s is the secondary stress intensity factor correction function
a is the crack size

K_{sb} is the self-balancing component of the residual stress profile

Table 1 shows some of the critical crack values (a_c) obtained at specific positions on the deck and for the 3 hypotheses of crack geometries being considered. For a correct interpretation it is necessary to take into account that in the case of through thickness cracks, a_c is the half-length of the defect observed in surface whereas in the semielliptical cracks the size of the crack width observed in surface is 2 and 10 times greater than a_c aspect ratios of 0.5 and 0.1, respectively.

Table 1. Critical crack values in joints.

Type of joint	PK or position	Plate	Stress (MPa)	Thickness (mm)	ac (mm) Through thickness crack	ac (mm) Semi elliptic crack (a/2c=0.5)	ac (mm) Semi elliptic crack (a/2c=0.1)
First and second types of joints (butt) (Longitudinal direction of the deck)	886	1	224	20	10.4	10.6	6.1
Third type of joints (variable thickness) (longitudinal direction of the deck)	886	1	224	20	10.4	10.6	6.1
Fourth type of joints (T-joints) (longitudinal direction of the deck)	886	1	224	20	13	10.6	6.1
First and second types of joints (butt) (Transverse direction of the deck)	Cable zone	4	310	12	7	3.4	1.8
Third type of joints (variable thickness) (Transverse direction of the deck)	Cable zone	4	310	12	7	3.4	1.8
Fourth type of joints (T-joints) (Transverse direction of the deck)	Cable zone	4	310	12	8.7	3.4	1.8

11. Conclusions

Within the framework of the inspection and maintenance plan of the Bridge of the Constitution of 1812 on the Bay of Cadiz, a section has been incorporated for the inspection of cracks in the deck, with special emphasis on specific points where the inspection must be more careful.

The result of the Structural Integrity Evaluation of the deck shows that the dimensions of the critical cracks have minimum values around 14 mm in the case of through thickness cracks, and around 6 mm for semielliptical cracks (assuming 0.5 as the aspect ratio).

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