Experimental Analysis of the Fatigue Strength of a Tubular Welded Joint adopted in a Roller Coaster Structure

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ABSTRACT. *The paper presents the practical aspects involved in structural design of roller coasters. Different design standards, commonly adopted in fatigue design of such structures, are considered and compared. The design loads, the detail categories and the main formulas for fatigue strength assessments are presented. Finally some constant amplitude fatigue tests are presented, which have been conduced for a typical tubular welded joint geometry.*

INTRODUCTION

Roller coasters are the most challenging amusement rides, under any aspect. From a structural point of view, two main types of roller coasters are currently operating in the amusement parks: steel roller coasters and wooden roller coasters. The former will be object of the analysis presented in this paper.

Considering a welded joint of the steel structure, every time that a wheel of a car approaches that joint, goes on top of it and departs from it, the joint will undergo a stress cycle, with a stress magnitude that will be initially increasing, reaching a peak and then vanishing. According to the kind of joint, stresses might generate pulsating fatigue or alternate fatigue.

If we consider the pictures of a typical roller coaster (Fig. 1), we can notice that tubular structures are frequently applied in this kind of construction. The cantilevered beams supporting the track are connected to the columns by means of welded joints that result generally very stressed and play a paramount role in the safety of the structure. Hence, this paper will concentrate the attention on such kind of joints.

To estimate the stresses in all the members and joints of the structure, detailed dynamic and stress analyses are requested. The solution of the motion equations allows to determine the history of forces applied at each point of the track. Then such forces must be transferred to a structural analysis of the whole structure.

Generally, a finite element model of the structure is defined, most of the times by means of one-dimensional elements (beams and links) and then analysed with proper load case conditions. The solution of such model allows to calculate the internal forces in the structural members and then the consequent nominal stresses at any point.

Figure 1. Typical welded structure adopted in a roller coaster manufacturing

CONVENTIONAL APPROACH TO THE FATIGUE ANALYSIS

The most traditional approach to the design of this kind of structures follows the recommendations of the German standard DIN 4112 [1], which generally regulates the amusement ride design; DIN4112, in turn, makes specific reference to the standard DIN 15018 [2], as far as the fatigue strength analysis of welded structures is concerned.

A more recent standard development, instead, refers to EN 13814 "Fairground and amusement park machinery and structures - Safety", as far as general rules are concerned, while refers to Eurocode 3 [3], when specific reference to the verification of steel structures, including fatigue of welded steel structures, is made.

Both such approaches, DIN- and EN-oriented, are mainly focused on nominal stresses (although Eurocode 3 opens a possibility to apply the "hot spot" approach).

The relevant fatigue strength verification procedures are roughly summarised in the following.

DIN 15018

The fatigue strength verification procedure, according to DIN 15018, is mainly based on:

- nominal stress values
- absolute maximum stress values
- fatigue ratio, defined as the algebraically minimum stress value in a point, divided by the maximum stress attained at the same point.

It leads to define an "allowable stress value", that corresponds to an endurance stress that should never be exceeded.

The allowable stress depends on:

- steel quality;

- loading group;
- notch class;
- fatigue ratio.

Steel quality
DIN 15018 considers two basic different types of weldable steels, St37 and St52, approximately equivalent to S235 and S355 according to EN 10025.

Loading group
DIN 15018 considers six groups of loading, namely B1, B2, B3, B4, B5 and B6, which are in turn determined according to the foreseen number of stress cycles N and the type of fatigue cycles, called stress collectives. DIN 4112 imposes to consider amusement rides in “Group B6”, since it requests to account for a service life with a number of cycles N exceeding 2 millions, corresponding to stress cycle range N4, and the heaviest idealized stress collective, corresponding to a history of constant maximum amplitude load cycles, that is S3.

Notch class
The notch class accounts for local stress concentrations due to the geometry and technological issues. DIN 15018 collects the types of connections and structural joints into eight notch classes, called W0, W1, W2, K0, K1, K2, K3 and K4, according to the notch effect caused by the particular geometry, connection technique, type of welding, weld surface finishing, post-welding controls (NDT) and loading condition of the component (weld seam loaded normal or parallel to its longitudinal axis, by normal stress or tangential stress). Classes identified by the W letter are related to single plates or bolted connections; those identified by the K letter are related to welded connections.

Fatigue ratio
As aforementioned, DIN 15018 accounts for the stress ratio. The procedure calculates the allowable stresses for each value of the fatigue ratio, starting from the value of fatigue resistance taken at a ratio $\chi = -1$ (i.e. completely reversed stress cycles). The fatigue strength data provided by DIN 15018 at $\chi = -1$ refer to a Wöhler curve corresponding to a survival probability of 90%, to which a further safety factor $\nu = 4/3$ is applied, for a final survival probability of 99.9%. The allowable values, obtained in case of cyclic loading of the component, must anyhow be considered also limited by the allowable values of static resistance or elastic stability.

The allowable normal fatigue stress “zul σ_D“ (zulässig = allowable) can be calculated at the different fatigue ratios according to proper formulas [2], paying attention whether the absolute maximum value of stress in the cycle corresponds to a tensile or compressive stress condition. In case of tangential stresses τ, the relevant allowable stress “zul τ_D” can be determined as a function of the corresponding zul σ_D value. In case of multi-axial stress condition, a proper interaction relationship involving stress components parallel and normal to the weld seam must also be fulfilled [2].

Finally it is important to underline that DIN 15018 cannot be applied to amusement rides without considering DIN 4112, which requires the application of two load factors, i.e. a minimum value of 1.2 as "impact factor" and a minimum value of 1.2 as "vibration factor" resulting in a global 1.44 load factor to amplify the theoretical dynamic loads.

At the end of this section, some remarks are worth to be highlighted:

- Frequently, the complex geometry of structural joints suggests the designer to develop "local" finite element models to have a reliable assessment of stresses. Such "local" models automatically account for some local stress risers (geometrical discontinuities, etc.), so the computed stress is no more a purely nominal stress. Nevertheless, DIN 15018 gives no guidance for local stresses, so the designer often considers such "local" stresses as nominal ones and this leads to some over-sizing of the structure.
- The endurance limit at 2 000 000 of cycles (Group B6), as stated in DIN 15018, cannot be always considered as a reliable endurance value, as proved by more recent studies and already accounted for in other standards.

Eurocode 3

When applying the nominal stress approach, the fatigue strength verification is performed according to the following criteria:

$$\gamma_{Ff} \cdot \Delta\sigma \leq \Delta\sigma_R / \gamma_{Mf} \ ; \qquad \gamma_{Ff} \cdot \Delta\tau \leq \Delta\tau_R / \gamma_{Mf}$$

where: $\Delta\sigma$, $\Delta\tau$ are the nominal stress ranges;

$\Delta\sigma_R$, $\Delta\tau_R$ are the fatigue strength ranges, identified according to the structural detail under examination and the design number of stress cycles;

γ_{Ff}, γ_{Mf} are respectively the load factor and material safety factor, to be applied for fatigue conditions.

As far as the allowable stress ranges are concerned, $\Delta\sigma_R$ and $\Delta\tau_R$, they are determined according to the following relationships:

$$\Delta\sigma_R^m \cdot N = \Delta\sigma_C^m \cdot 2e^6 \Leftrightarrow N \leq 10^8 \ ; \qquad \Delta\tau_R^m \cdot N = \Delta\tau_C^m \cdot 2e^6 \Leftrightarrow N \leq 10^8$$

where: $\Delta\sigma_C$, $\Delta\tau_C$ are constant amplitude stress ranges, related to a particular detail category, for an endurance $N=2x10^6$ cycles; their values identify the different detail category numbers in the relevant tables;

m is the slope of the fatigue S-N strength curve;

Reference should be made to the fatigue curves given by the Standard to calculate $\Delta\sigma_R$ and $\Delta\tau_R$ according to the number of cycles. The fatigue curves are referred to a 95% survival probability.

Furthermore, Eurocode 3 requires to account for the size effect due to thickness or other dimensional effects, leading to down-graded detail categories: $\Delta\sigma_{C,\,red} = k_s\ \Delta\sigma_C$, $\Delta\tau_{C,red} = k_s\ \Delta\tau_C$.

When dealing with amusement rides, Eurocode 3 must be applied together with EN 13814, which defines different material safety factor ranging from 1 up to 1.15 depending on whether the structural detail is accessible or not and whether the rupture will cause the collapse of the entire structure or not.

As far as the load factor γ_{Ff} is concerned, EN 13814, as well as DIN 4112, requires the application of two load factors, 1.2 as "impact factor" and 1.2 as "vibration factor" resulting in a global 1.44 load factor to amplify the theoretical dynamic loads.

In case of combined stress ranges, and interaction formula must be fulfilled [3], while in case of load histories with variable amplitude, the fatigue strength verification can be carried out accounting for the "cumulative damage", according to the Palmgren-Miner's law.

The allowable values, obtained in case of cyclic loading of the component, must anyhow be considered also limited by the allowable values of static resistance or elastic stability.

At the end of this section, some remarks are also worth to be highlighted:

- In case of the complex geometry of structural joints, Eurocode 3 suggests the hot spot approach as a "local approach", to overcome the nominal stress approach, although several doubts have been raised about the reliability of the hot spot method.
- Eurocode 3 accounts for the size effect, that represents an important physical factor in any structural element subject to fatigue condition.
- Eurocode 3 deals with stress ranges, so, differently from DIN, it does not account for the mean stress in as welded structures.
- The application of the cumulative damage law requires a computation of the number of cycles (n_i) at each stress range amplitude level; in amusement rides, a precise counting of cycles is frequently highly troublesome, that makes such approach quite difficult and often disliked by designers.

As a final conclusion of this section, after shortly describing these two conventional approaches, it can be noticed that a direct comparison between DIN 15018 and Eurocode 3 is almost impossible from the designer's point of view. Surely DIN starts from a higher basic requirement of survival probability (99.9%), but Eurocode 3 includes the effect of higher endurance limits, of variable amplitude cycles, of the size factor, that are also very severe. Moreover, the different approach based on the maximum stress value (DIN 15018) or the stress range (Eurocode 3) creates another significant divergence.

Nevertheless, both procedures are mainly based on the nominal stress approach: DIN totally ignores a possible way for the designer to cope with "local" stresses, Eurocode 3 offers a disputable hot spot method, with very poor instructions about a proper application method. On the contrary, the modern design technique leads more and more to develop detailed local stress analyses and claims for a reliable approach that allows to deal with such values.

EXPERIMENTAL FATIGUE TESTS

Fatigue tests were conduced on four specimens consisting of a cruciform 10-mm-thick tubular welded joint adopted in the roller coaster structure. The geometry of the tested joints is reported in Fig. 2. The outer diameter of the adopted Fe510 steel tubes was 101.6 mm. Two braces were symmetrically welded on a chord tube through 12x12 full penetration MIG welds. A dedicated loading frame was designed and manufactured in order to apply bending loads to both braces of the tubular joint, as depicted in Fig. 3. The load ratio was set equal to 0.1 and a servo-hydraulic axial MFL test machine equipped with a load cell of 250 kN was adopted.

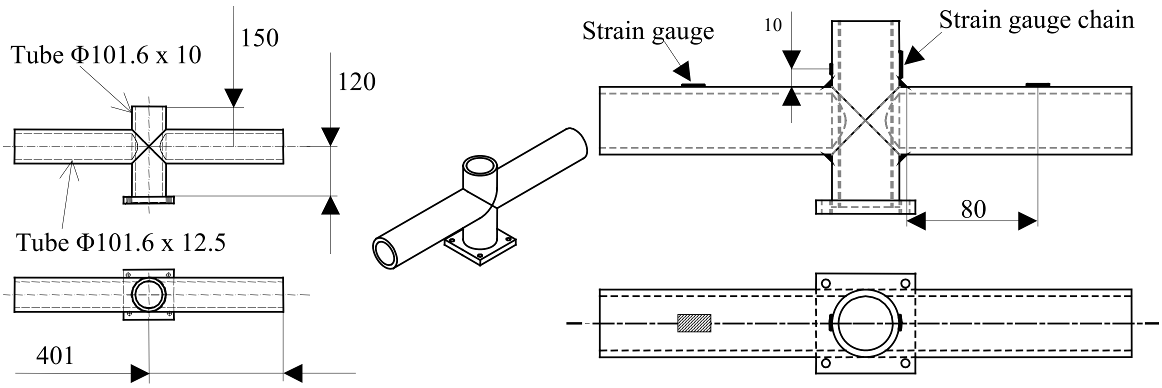

Figure 2. Geometry of the tested tubular welded joints.

In order to verify that the joint was symmetrically loaded, two strain gauges were applied, one for each brace tube, 80 mm far from the weld toe, as reported in Fig. 2. Such strain gauges measured the applied nominal strain. Moreover the structural stress field was experimentally analysed by means of a HBM KY 11 1/120 strain gauge chain, consisting of ten 1-mm-long uniaxial strain gauges. The total length of the strain gauge chain was 11 mm and it was applied close to the weld toe of the chord tube, since that was seen to be the location of crack initiation during the experimental tests. Strains were measured by means of a HBM UPM 100 data logger after having statically applied the maximum load reached in all the fatigue tests.

During fatigue tests, cracks were seen to initiate at the crown point of the chord tube and then propagated into the depth and along the weld toe up to the saddle points, as shown by Fig. 3. When the crack reached the saddle points, the joints' stiffness was completely lost, so that the final fracture was identified. During the fatigue tests, the stiffness was measured by monitoring the minimum actuator displacement. According to the available experimental set-up, a decrease in the minimum actuator displacement means a decrease in the joint's stiffness. As an example Figure 4 shows a typical displacement vs number of cycles curve observed during the experimental tests: it is seen that a significant fraction of the fatigue life is spent in crack propagation, which progressively reduce the joint's stiffness before the final fracture occurs. Then, from an engineering point of view, the number of cycles up to crack initiation N_i was identified in correspondence of the initial stiffness drop, as shown by Fig. 4.

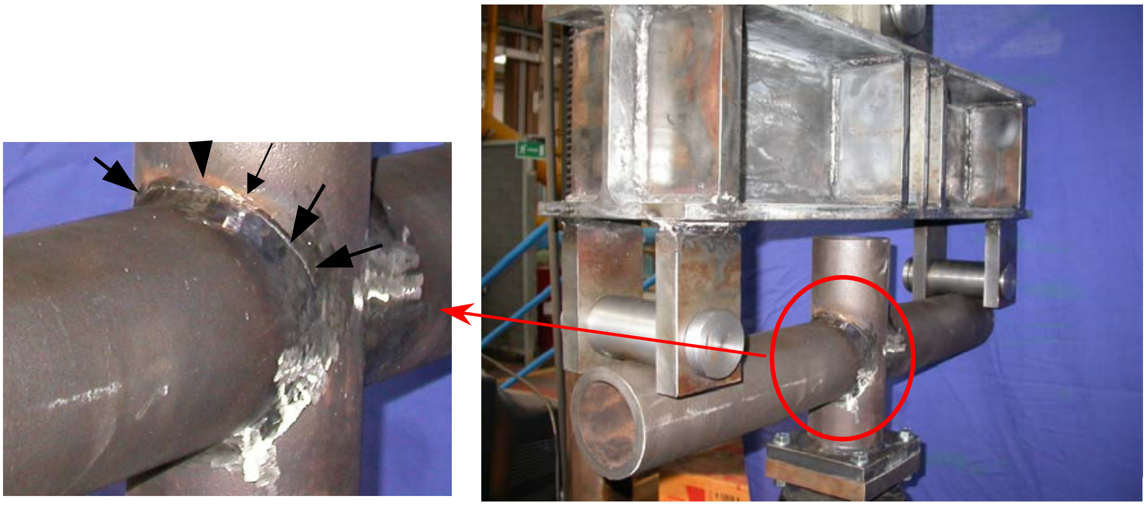

Figure 3. Adopted loading frame in the three point bending tests and typical crack propagation path observed after the fatigue test.

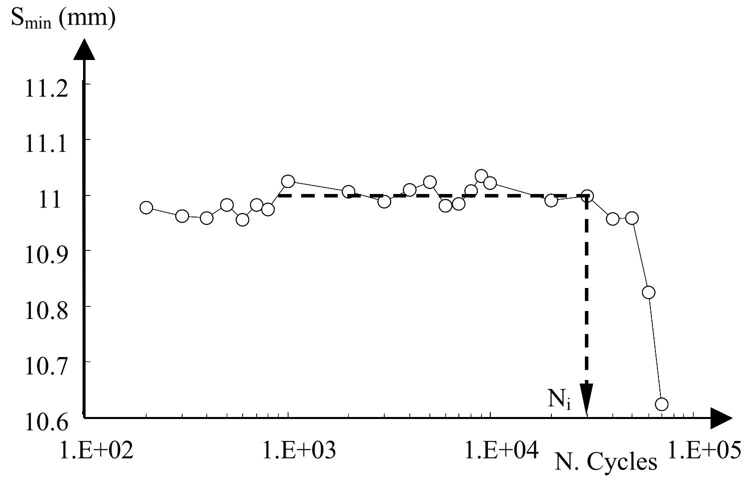

Figure 4. Typical stiffness drop measured during the experimental tests and engineering definition of fatigue life to crack initiation.

The experimental results reported in Fig. 5 are shown by means of two markers for each fatigue test. The open markers refer to the number of cycles to crack initiation N_i. Filled markers refer to the number of cycle corresponding to a complete stiffness loss and it corresponded to the presence of a through the thickness crack involving about half of the weld toe line (i.e. from the crown point to the saddle points in the chord tube). The reported scatter band is that estimated on the basis of the so-called Peak Stress Method, that has been recently devised [4].

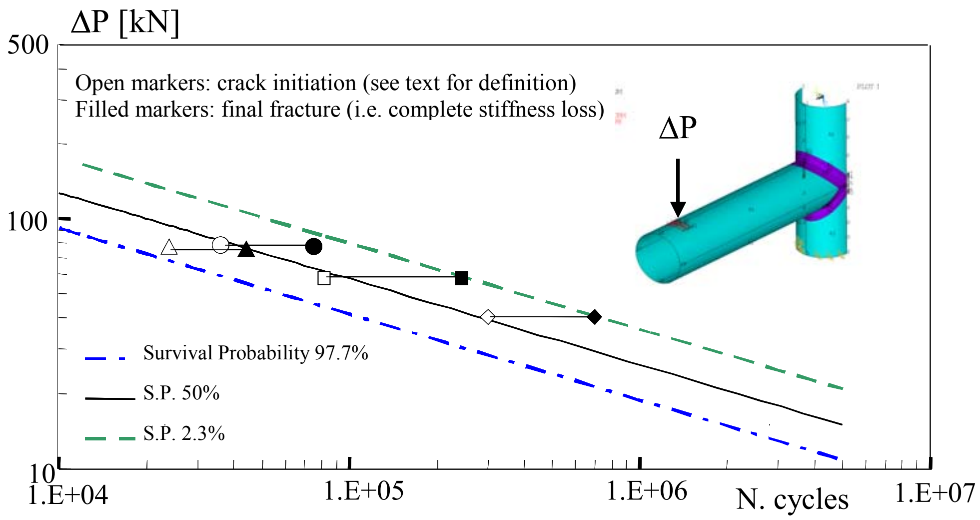

Figure 5. Fatigue test results of tubular welded joints. The scatter band is not a best fit of the experimental results.

CONCLUSIONS

The paper has presented some topics that a design engineer has to deal with when performing fatigue strength assessment of structures for amusement rides. Among these, roller coasters have been analysed in detail by considering the loads, the detail categories and the design formulas proposed by the Standards in force. Finally the fatigue tests conducted on a typical tubular welded joint geometry adopted in roller coasters manufacturing highlighted that a significant fraction of the total fatigue life is spent in crack propagation, which can be distinguished from the crack initiation phase.

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