Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 19 (2019) 627–636

Structural Integrity Procedia

www.elsevier.com/locate/procedia

Fatigue Design 2019

Definition of nominal stress-based FAT classes of complex welded steel structures using the Peak Stress Method

Michele Zanetti[a,b], Vittorio Babini[b], Giovanni Meneghetti[a]*

[a] *Department of Industrial Engineering, University of Padova, Via Venezia, 1 – 35131 Padova (Italy)*
[b] *Antonio Zamperla Spa, via Monte Grappa 15/17, 36077, Altavilla Vicentina (VI)*

Abstract

The purpose of this paper is to report some industrial applications of the local approach Peak Stress Method (PSM) in fatigue strength assessment of complex welded steel joints adopted in amusement park structures, focusing on roller coasters. This method is an application of the N-SIFs approach and it is based on the singular, linear elastic peak stresses calculated from FE analyses with coarse free meshes.

For fatigue strength assessment of large structures like roller coasters, companies often prefer using FE beam models and compare nominal stresses with fatigue strength values (FAT classes) available in design standards.

Roller coasters present many types of complex welded joints that differ in (i) technological parameters, e.g. weld penetration, and (ii) geometrical parameters, e.g. track pipes number, shape and number of connection elements between track pipes (tie beam, cross beam, lattice structures, etc.). Due to complex geometries and limited number of FAT classes available in design standards, finding appropriate FAT classes consistent with the real geometries is frequently troublesome. To overcome this problem, in this paper some applications of the mentioned local approach are proposed; the outcome is the definition of FAT classes in terms of nominal stress starting from the design curve calibrated in the context of the PSM. The advantage is that it is possible to perform FE analysis with beam elements, having in hands FAT classes derived from a robust local approach and faithful to real geometries.

Peer-review under responsibility of the Fatigue Design 2019 Organizers.

Keywords: welded joints, Peak Stress Method (PSM), FAT class

* Corresponding author. Tel.: +390498276751; fax: +390498276785.
E-mail address: giovanni.meneghetti@unipd.it

2452-3216
Peer-review under responsibility of the Fatigue Design 2019 Organizers.
10.1016/j.prostr.2019.12.068

1. Introduction

In design standards and recommendations are available different design approaches in order to assess the fatigue strength of welded joints: the nominal stress, the hot spot stress, the fictious notch rounding and the Linear Elastic Fracture Mechanics (LEFM) approaches [1, 2]. The nominal stress approach is simple to use, in that stresses are calculated from the beam theory. However, detail categories, i.e. FAT classes, must be available for each geometry of the joint. Design standards and recommendation collect several categories and provide the nominal stress-based design curve, along with the correction factors to account for thickness and/or shape effects, if applicable. In this context, local approaches aim at local stresses to design against fatigue, in order to include in the stress analysis all effects of welded joint geometry (shape effect) and absolute dimensions (scale effect). Notch-stress intensity factors (N-SIFs) proved to be effective, linear elastic, local stress parameters for fatigue design of welded joints [3-4]. Subsequently, a FE-based method, called Peak Stress Method (PSM), has been proposed [5-6] to calculate rapidly the NSIFs with 2D or 3D FE analyses using a coarse mesh.

Even if the PSM proved to be effective and robust, nevertheless private companies often need simple finite element beam models for fatigue strength assessments, because of the large dimensions of the structures, which makes it difficult to use shell or three-dimensional FE models. Therefore, the nominal stress approach based on FAT classes is adopted. However, finding appropriate FAT classes consistent with the analysed welded joint geometry is frequently troublesome, particularly when complex geometries are treated.

The main objective of this work is to define new FAT classes in terms of nominal stress for a number of geometrically complex welded structural details in structural steel, starting from the master design curve defined in previous papers in terms of local equivalent peak stress, according to PSM.

The content of this paper could be summarised as follows: (i) description of methods used (PSM) from a theorical point of view, (ii) description of procedure adopted to determine FAT classes for structural details and (iii) presentation and discussion of results.

In the last part of this paper a case study is proposed, where fatigue strength assessment of welded joints belong to a lattice structure is performed using directly the local approach, i.e. the Peak Stress Method. This represent an example of how the PSM could be implemented directly in industry to assess the fatigue strength of geometrically complex welded joints. Structural details analysed in this paper are typically adopted in amusement park structures and in several cases they are not classified in design standards for steel structures.

2. Peak Stress Method: theoretical background

2.1. Peak Stress Method (PSM) and extension to ten-node tetra finite elements

The Peak Stress Method (PSM) is an engineering, FE-oriented application of the notch stress intensity factor (NSIF) approach to fatigue design of welded joints, which assumes both the weld toe and the weld root as sharp V-notches, having a notch tip radius ρ= 0 and a notch opening angle $2\alpha \geq 0°$ (typically 135° for weld toe and 0° for weld root). Under these assumptions, the local, linear elastic stress fields in the vicinity of the notch tip depends on the relevant NSIFs, which quantify the magnitude of the asymptotic singular stress distribution. However, applying the NSIF approach requires extremely fine FE meshes at the notch tip (element size on the order of 10^{-5} mm) and therefore requires very long time for mesh generation, model solution and analysis of results. Consequently, direct evaluation of local stresses can hardly be applied in the industry to solve structural engineering problems.

To attack this problem, the Peak Stress Method (PSM) has been proposed [5], see Figure 1, in order to estimate the NSIFs K_1, K_2 and K_3 by adopting the singular, linear elastic, opening (mode I), sliding (mode II) and tearing (mode III) peak stresses $\sigma_{\theta\theta,\theta=0,peak}$, $\tau_{r\theta,\theta=0,peak}$ and $\tau_{\theta z,\theta=0,peak}$, respectively calculated at the notch tip from FE analyses with coarse meshes, if compared to the very refined mesh required to evaluate the NSIFs. The polar frame of reference (r,θ) is referred to the V-notch bisector line, as depicted in Fig.1. The estimated NSIFs values can be obtained from the following expressions [5, 7, 8]:

$$K_1 = K_{FE}^{*} \cdot \sigma_{\theta\theta,\theta=0,peak} \cdot d^{1-\lambda_1} \quad (1)$$

$$K_2 = K_{FE}^{**} \cdot \tau_{r\theta,\theta=0,peak} \cdot d^{1-\lambda_2} \quad (2)$$

$$K_3 = K_{FE}^{***} \cdot \tau_{\theta z,\theta=0,peak} \cdot d^{1-\lambda_3} \tag{3}$$

where d is the '*global element size*', i.e. the average FE size adopted by free mesh generation algorithm available in FE software; parameters λ_i are the mode I, II and III eigenvalues which are dependent on the notch opening angle 2α; parameters K_{FE}^{*}, K_{FE}^{**} e K_{FE}^{***} depend on the calibration options: (i) element type and formulation, (ii) mesh pattern and (iii) procedure for stress extrapolation at FE nodes.

Originally, the PSM has been calibrated to 2D four-node plane elements available in Ansys® library and the following results were found: (i) K_{FE}^{*}=1.38; (ii) K_{FE}^{**}=3.38 and (iii) K_{FE}^{***}=1.93 under conditions reported in [5, 7 8], to which the reader is referred. Later on, the PSM has been extended to eight-node 3D brick elements [9] obtained from mesh extrusion. More recently, to broaden the applicability of the PSM, parameters K_{FE}^{*} and K_{FE}^{**} have been also calibrated by adopting six commercial FE packages other than Ansys® [10].

Since the units of NSIFs depend on the notch opening angle 2α, fatigue assessments of weld roots and toes cannot be performed by a direct comparison of NSIF values. This problem was overcome by using the total elastic strain energy (SED) averaged over a sector of radius R_0 surrounding the weld toe and the weld root. For a complete discussion of the method see [11-15].

Considering a general multiaxial load condition (mixed mode I, II and III), by using the PSM relationships (Eq. (1)-(3)), the closed-form expression of averaged SED re-converted to an equivalent uniaxial stress can be rewritten as function of the singular, linear elastic FE peak stresses as follows [13]:

$$\Delta\sigma_{eq,peak} = \sqrt{c_{w1} \cdot f_{w1}^2 \cdot \Delta\sigma_{\theta\theta,\theta=0,peak}^2 + c_{w2} \cdot f_{w2}^2 \cdot \Delta\tau_{r\theta,\theta=0,peak}^2 + c_{w3} \cdot f_{w3}^2 \cdot \Delta\tau_{\theta z,\theta=0,peak}^2} \tag{4}$$

where f_{wi} (i = 1, 2, 3) are known parameters, which have been defined in detail in [5, 7, 8]and coefficients c_{wi} (i = 1, 2, 3) are known correction factors, which are to be used only in case of stress relieved joints and depend on the applied stress ratio [13].

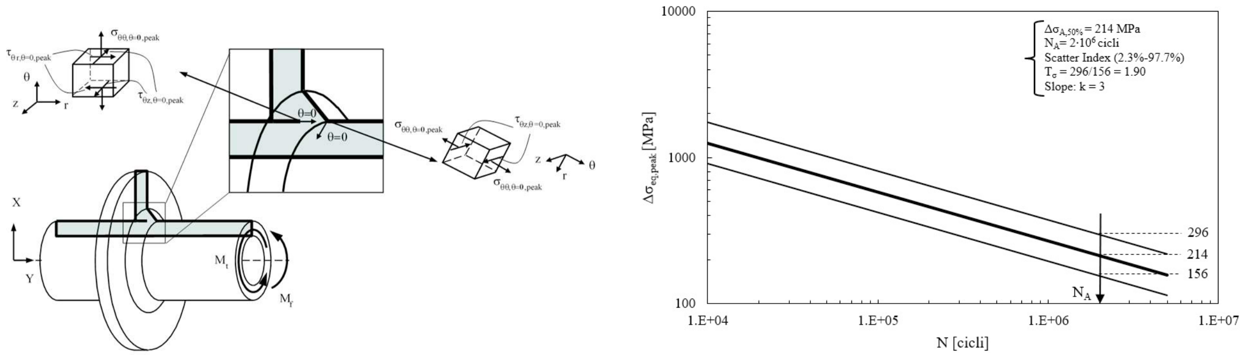


Figure 1: On Left: typical pipe-flange welded joint under multiaxial fatigue loading with the respective linear elastic peak stress components at the weld toe and the weld root. On Right: Scatter band in terms of equivalent peak stress calibrated by using approximately 1000 data relevant to weld and toe failures for arc-welded joints loaded with mode I+II [16-17].

The scatter band reported in Figure 1 is expressed in terms of range of the equivalent peak stress (Eq. (4)) and it has been originally calibrated by using approximately 180 well documented experimental results taken from the literature. The design scatter band reported in Figure 1 has been successfully validated on approximately 1000 experimental results relevant to weld toe and weld root failures for steel arc-welded joints, in as-welded conditions and subjected to mode I+II loads and multiaxial loads [16, 17].

3D modelling of large-scale structures is increasingly adopted in industrial applications, thanks to the growing spread of high-performance computing (HPC). PSM has been recently calibrated also for 10-nodes tetra elements (SOLID 187 in Ansys®) [18]. Meshing with tetra element proved to be able to discretize large and complex 3D structures making the PSM applicable directly to a single model.

When adopting tetrahedral elements, the mesh pattern is intrinsically irregular, so an average peak stress value has been proposed by applying a moving average over three adjacent vertex nodes. Alternatively stated, the average peak stress at node n=k is defined as (n=k-1 e n=k+1):

$$\bar{\sigma}_{ij,peak,n=k} = \left.\frac{\sigma_{ij,peak,n=k-1} + \sigma_{ij,peak,n=k} + \sigma_{ij,peak,n=k+1}}{3}\right|_{n=node} \quad (5)$$

Table 1 reports constants K^{*}_{FE}, K^{**}_{FE} e K^{***}_{FE} calibrated for ten-node tetra elements [18] and hypothesis of validity depending of notch opening angle (2α).

			Limitations of applicability	
			2α	***a/d***
Mode I	K^{*}_{FE}	1.01 ± 15%	0°, 90°	≥ 3
		1.21 ± 10%	135°	≥ 1
Mode II	K^{**}_{FE}	1.63 ± 20%	0°	≥ 1
Mode III	K^{***}_{FE}	1.37 ± 10%	0°	≥ 2
		1.75 ± 5%	135°	≥ 2

Table 1: Summary of calibration of K^{*}_{FE}, K^{**}_{FE} and K^{***}_{FE} for 10-node tetrahedral elements (SOLID 187 of Ansys®).

3. FAT classes for un-classified welded joint geometries

As mentioned before, welded details in structural steel, which are typically adopted in amusement park structures, are considered in this paper. Table 2 presents the analysed geometries with their main dimensions.

For each geometry fatigue classes (FAT) in terms of applied nominal stress have been defined starting from the design curve defined in terms of PSM (§3.1).

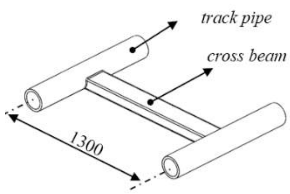
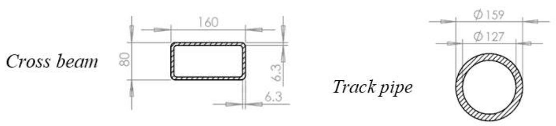
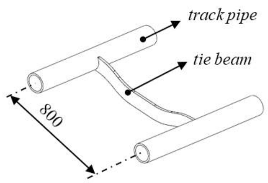
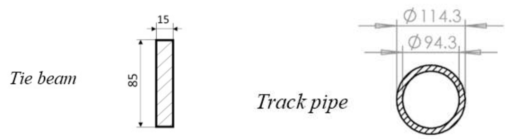
Nomenclature	Geometry and components	Principal dimensions
(1) two track pipes and cross beam		
(2) two track pipes and tie beam		

Table 2: Analysed geometries (dimensions in [mm]).

FAT classes have been defined for each elementary loading condition acting on the welded joint, i.e. by axial stress or in plane as opposed to out of plane bending moment acting on the track pipe or on the cross beam/tie beam. Table 3 shows in detail the loading conditions and the relevant nomenclature adopted in this paper.

For each geometry (i) full-penetration welds as well as (ii) fillet welds have been considered in order to assess the fatigue criticality of the weld root as compared to the weld toe, whenever possible.

3.1. Definition of fatigue strength classes adopted Peak Stress Method

The general approach applied to determine FAT classes is summarized in following points.

- Modelling of component’s geometry according to PSM application.

– Application of constraints/loads and meshing with 10-node tetra elements imposing a global element size compatible with the hypothesis of validity shown in Table 1.

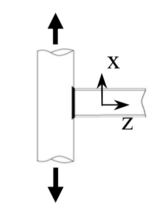
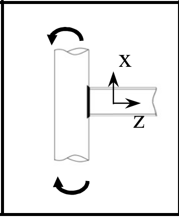
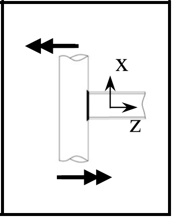
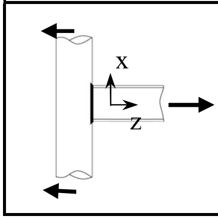
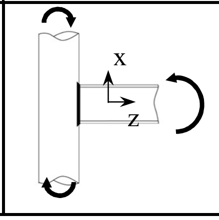
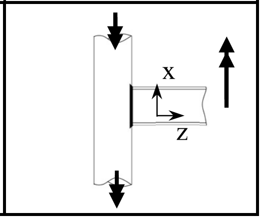
Loads condition acting on track pipe			Loads condition acting on cross/tie beam		
axial load track pipe	*in plane bending track pipe*	*out of plane bending track pipe*	*axial load cross/tie beam*	*in plane bending cross/tie beam*	*out of plane bending cross/tie beam*
axP	**ipbP**	**opbP**	**axC / axT**	**ipbC / ipbT**	**opbC / opbT**
F_x	M_y	M_z	F_z	M_y	M_x
					

Table 3: Elementary loading conditions acting on the welded connections.

– Evaluation of the three linear elastic peak stresses ($\sigma_{\theta\theta,\theta=0,peak}$, $\tau_{r\theta,\theta=0,peak}$ and $\tau_{\theta z,\theta=0,peak}$) along three paths that represent weld toe of the track pipe, weld toe of the cross/tie beam and weld root if applicable. The average value at each node has been calculated by means of Eq. (5) and after that the three components are combined in order to obtain the equivalent peak stress.

– The maximum value of the detected average equivalent peak stress is used to define the fatigue strength class (FAT) with the following expression:

$$\mathrm{FAT} = \frac{\Delta\sigma_{\mathrm{nom}} \cdot \mathrm{FAT}_{\mathrm{PSM}}}{\overline{\Delta\sigma}_{\mathrm{eq,peak,max}}} \tag{6}$$

where:

- $\Delta\sigma_{\mathrm{nom}}$ is the nominal stress referred to loaded component and calculated with the known formulas: $\frac{F}{A}$ for axial force and $\frac{M}{W_f}$ for bending, where area (A) and section modulus (W_f) are referred to net cross-section of component (see Table 2).
- $\mathrm{FAT}_{\mathrm{PSM}}$ is the fatigue class at 2 million cycles and survival probability of 97.7% valid of the equivalent peak stress-based fatigue curve; figure 1 shows that $\mathrm{FAT}_{\mathrm{PSM}}$=156 MPa.

Table 4 reports an example of application of the procedure described above in order to determine the fatigue strength classes using Peak Stress Method. The example reported refers to following conditions:

– geometry: 2 track pipes with cross beam (Table 2);
– weld condition: fillet weld;
– load: cross beam loads with in plane bending (*ipbC* - Table 3).

All the load conditions shown in Table 3 have been applied to each geometry shown in Table 2, following the procedure described in Table 4.

4. Results and discussion

All results obtained have been summarized in Table 5 in terms of FAT classes calculated starting from the Peak Stress Method (for full penetration and fillet weld). For comparison purposes, FAT classes have been determined also from available Design Standards and in particular Eurocode 3 [1] and UNI EN 13001 [19]. However, it is worth noticing that the FAT classes available in [1, 19] do not faithfully reproduce the geometry of the real welded details considered in the present paper. Table 5 reports also the position of the critical point anticipated by the PSM. The adopted nomenclature recalls the following locations of the critical point: track pipe weld toe (P), backbone weld toe (B), weld root (R), cross beam weld toe (C) and tie beam weld toe (T); in cases of two equally critical points, both of them are indicated in Table 5.

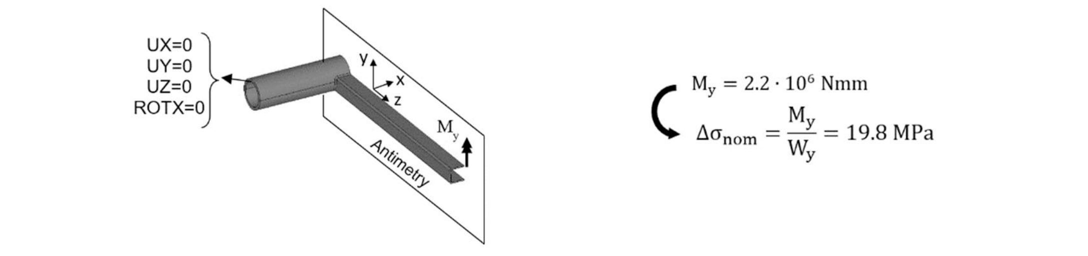
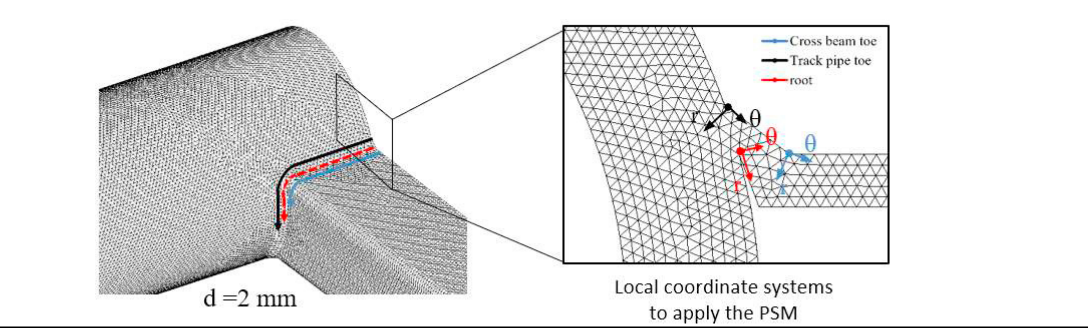
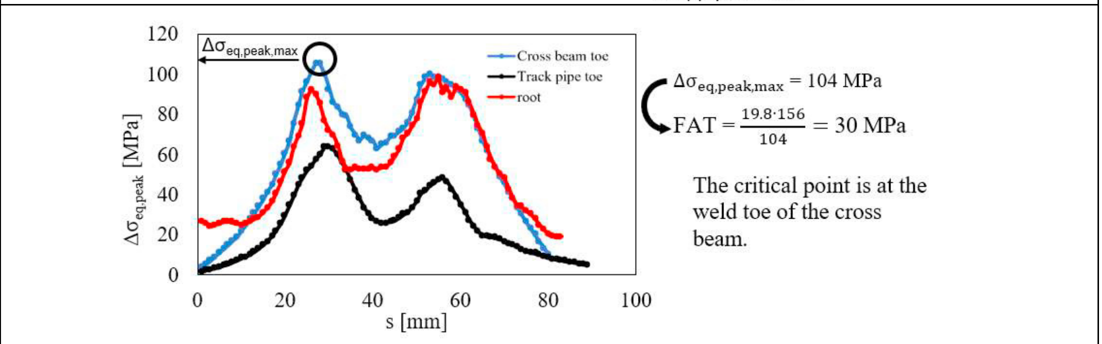
Loads and constraints definition	
Results analysis and FAT* calculation	
Results analysis and FAT* calculation	

Table 4: Example of the method used to calculate FAT classes adopting the PSM.

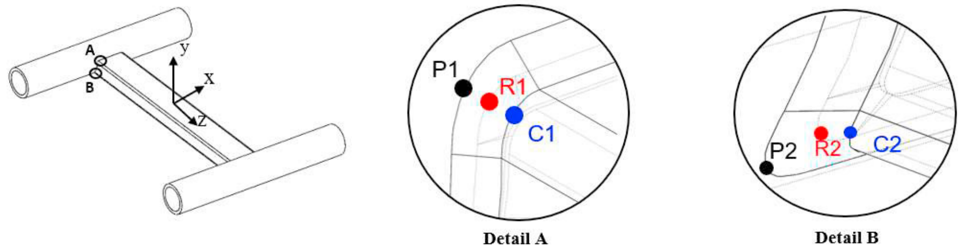
It is noted that in results as not been reported load conditions 'out of plane bending' for track pipe, referred to Table 3, because they are not considered the most critical loading conditions.
Some remarks that emerges from results reported in Table 5 can be stated as follows.

- FAT classes taken from Design Standards are higher than those obtained from the PSM approach. This is due to the difficulty to find the appropriate geometry in the Design Standards, which is consistent with the analysed detail, in particular when geometries are complex.
- The PSM allows to evaluate comparatively the fatigue criticality at the toe and at the root (fillet or partial penetration weld).
- From results obtained adopting PSM emerges that, for several loading conditions (in particular for load-carrying fillet welds: *axC/axT, ipbC/ipbT, opbC/opbT*), a fillet weld leads to a reduction of the fatigue strength class as compared to a full penetration weld (from 15% to 25%). It is also observed that the weld root is never the most critical point.

- **Direct application of PSM**

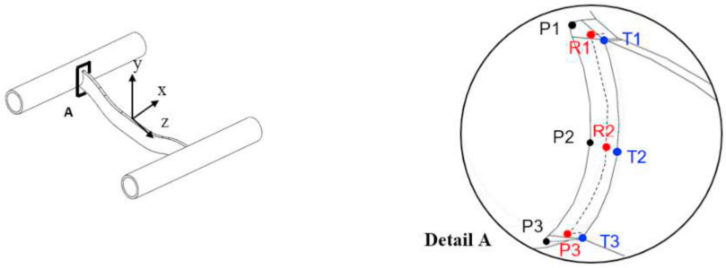
After reporting on the use of the PSM to estimate FAT classes in terms of nominal stress, a case study describing the direct application of the PSM is reported in this section, to tackle the fatigue strength assessment of two geometrically complex welded joints of a lattice-type connection (node A and node B of Figure 2). Figure 2 reports the loading condition studied, which consist of 4 vertical forces (40 kN each) applied to track pipes.

(1) two track pipes with cross beam



Load condition [Table 3]	PSM				STANDARDS	
	Full penetration		Fillet weld			
	Critical point	FAT [MPa]	Critical point	FAT [MPa]	FAT [MPa]	Reference
axP	*P2*	50	*P2*	47	63	Table H.1.12 [21]
ipbP	*P1*	46	*P1*	45		
axC	*C1*	34	*C1*	29	50	Table H.1.13 [21]
ipbC	*C1*	39	*C1*	30		
opbC	*C2*	34	*C2*	26		

(2) two track pipes with tie beam



Load condition [Table 3]	PSM				STANDARDS	
	Full penetration		Fillet weld			
	Critical point	FAT [MPa]	Critical point	FAT [MPa]	FAT [MPa]	Reference
axP	*P2*	67	*P2*	67	71	Table 8.4 [1]
ipbP	*P2*	66	*P2*	65		
axT	*T1*	21	*T1/R1*	19	80	Table 8.5 [1]
ipbT	*T2*	71	*T2*	60		
opbT	*T1*	41	*T1*	37		

Table 5: FAT values for the analysed geometries and load conditions.

4.1. FE modeling and analysis procedure

The procedure adopted for fatigue assessment of nodes A and B (Figures 2) can be summarized as follows.

– 3D Modelling the welded joints and meshing with 10-node tetra elements in compliance with the conditions of applicability of the PSM, as reported in Table 1.
– Evaluation of the three linear elastic peak stresses components ($\sigma_{\theta\theta,\theta=0,peak}$, $\tau_{r\theta,\theta=0,peak}$ and $\tau_{\theta z,\theta=0,peak}$), evaluation of the average stress components according to Eq. (5) and their combination (Eq. (4)) in order to obtain the average equivalent peak stress along weld toe lines.
– The maximum value of the equivalent peak stress is used to perform the fatigue assessment defining a safety factor (SF) at 5 million cycles:

$$SF = \frac{\overline{\Delta\sigma}_{eq,peak,max}}{\Delta\sigma_D} \tag{7}$$

where: $\Delta\sigma_D$ is the fatigue strength at 5e6 cycles valid for the design curve expressed in terms of equivalent peak stress (Figure 2), in particular $\Delta\sigma_D$=156·0.737 = 114.9 MPa.
The fatigue assessment is satisfied if: SF> 1.

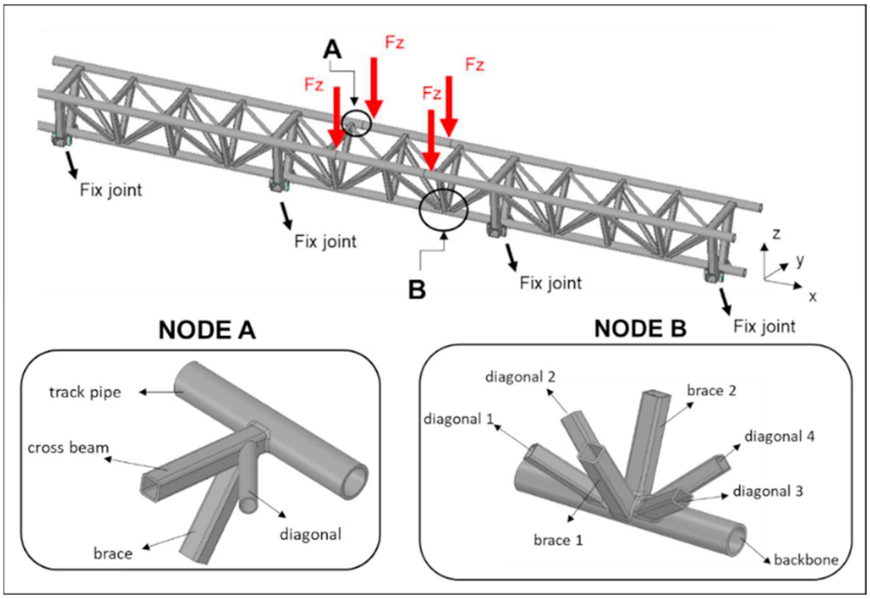


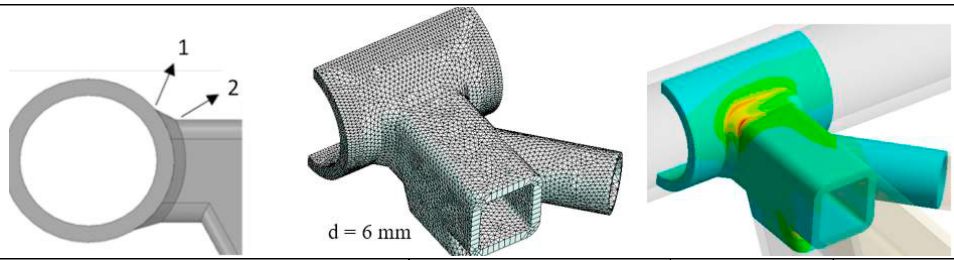
Figure 2 Lattice structure with loads and restraint and details of nodes analysed with the PMS.

4.2. Results

Results obtained from analysis are reported in Table 6 (for NODE A) and Table 7 (for NODE B).

- NODE A. Is possible to distinguish two potential critical points: the weld toe on the track pipe side and the weld toe on the cross beam side. Table 6 reports the results of fatigue assessment at two critical points and also a plot of the maximum principal stress, where it is seen that the most critical position is located at the weld toe of the cross beam. The NODE A is verified with a SF of 1.85.
- NODE B. By plotting the maximum principal stress (Table 7), it is seen that there are two potential critical points: the weld toe on the brace side (1) and the weld toe on the diagonal side (2). However, the average equivalent peak stress is higher at the weld toe of the brace, where the fatigue strength is assessed with a SF of 1.20.

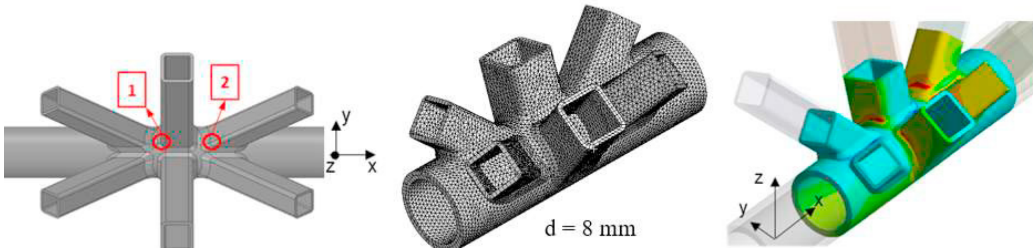
NODE A



Position	$\Delta\sigma_{eq,peak,max}$ [MPa]	SF	Verification
Weld toe track pipe side (1)	58.1	1.98	**OK**
Weld toe cross beam side (2)	62.1	1.85	**OK**

Table 6: Results of fatigue strength assessment for NODE A of lattice structure (Figure 2).

NODE B



Position	$\Delta\sigma_{eq,peak,max}$ [MPa]	SF	Verification
Weld toe brace side (1)	95.9	1.20	**OK**
Weld toe diagonal side (2)	80.3	1.43	**OK**

Table 7: Results of fatigue strength assessment for NODE B of lattice structure (Figure 2).

5. Conclusions

In this paper a method to estimate the FAT classes in terms of nominal stresses starting from the existing design curve of the Peak Stress Method (PSM) has been proposed. The aim is to perform FE analyses of geometrically complex welded structures by adopting beam elements, but at the same time by using FAT classes derived from a robust local approach and faithful to the real geometry.

FAT classes can be determined also by adopting other existing approaches, for example the Hot Spot Stress approach or the Notch Stress approach. However, the present analysis highlights the advantage of using the PSM instead other approaches in terms of the simplicity of use and time saving. This is made possible by the use of the PSM calibrated for ten-node tetrahedral elements, which allows to use relatively coarse meshes and, more important, to discretise any type of geometry imported directly from a CAD software.

At last, a case study has been proposed, where the PSM has been applied directly for fatigue strength assessment of some complex welded joints. To the authors' opinion, the Peak Stress Method might be useful in industrial applications to assess the fatigue strength of welded joints. In this paper welded details adopted in amusement park structures have been considered.

References

[1] Eurocode 3: Design of steel structures – part 1–9: Fatigue. CEN; 2005.

[2] Hobbacher AF. Recommendations for Fatigue Design of Welded Joints and Components. IIW Collection. Springer International Publishing; 2016.

[3] Lazzarin P, Tovo R. A notch intensity factor approach to the stress analysis of welds. Fatigue Fract Eng Mater Struct 1998; 21:1089–103.

[4] Lazzarin P, Livieri P. Notch stress intensity factors and fatigue strength of aluminium and steel welded joints. Int J Fatigue 2001;23:225–32

[5] Meneghetti G, Lazzarin P. Significance of the elastic peak stress evaluated by FE analyses at the point of singularity of sharp V-notched components. Fatigue Fract Eng Mater Struct 2007; 30:95–106.

[6] Meneghetti G, Lazzari P. The Peak Stress Method for Fatigue Strength Assessment of welded joints with weld toe or weld root failures. Weld. World 2011; 55:22-29.

[7] Meneghetti G. The use of peak stress method for fatigue strength assessments of welded lap joints and cover plates with toe and root failures, Eng. Fract. Mech 2012; 89:40-51.

[8] Meneghetti G. The peak stress method for fatigue strength assessment of tube-to-flange welded joints under torsion loading. Weld World 2013; 57:265–75.

[9] Meneghetti G, Guzzella C. The peak stress method to estimate the mode I notch stress intensity factor in welded joints using three-dimensional finite element models. Eng Fract Mech 2014; 115:154–71.

[10] G. Meneghetti, A. Campagnolo, M. Avalle, D. Castagnetti, M. Colussi, P. Corigliano, et al. Rapid evaluation of notch stress intensity factor using the peak stress method: comparison of commercial finite element codes for a range of mesh patterns. Fatigue Fract. Eng. Mater. Struct. 2017; 41:967-1242.

[11] Lazzarin P, Zambardi R. A finite-volume-energy based approach to predict the static and fatigue behavior of components with sharp V-shaped notches. Int J Fract 2001; 112:275–98.

[12] Lazzarin P, Livieri P, Berto F, Zappalorto M. Local strain energy density and fatigue strength of welded joints under uniaxial and multiaxial loading. Eng Fract Mech 2008; 75:1875–89.

[13] Lazzarin P, Sonsino CM, Zambardi R. A notch stress intensity approach to assess the multiaxial fatigue strength of welded tube-to-flange joints subjected to combined loadings. Fatigue Fract Eng Mater Struct 2004; 27:127–40.

[14] Lazzarin P, Lassen T, Livieri P. A notch stress intensity approach applied to fatigue life predictions ofwelded joints with different local toe geometry. Fatigue Fract Eng Mater Struct 2003; 26:49–58.

[15] Livieri P, Lazzarin P. Fatigue strength of steel and aluminium welded joints based on generalised stress intensity factors and local strain energy values. Int J Fract 2005; 133:247–76.

[16] Meneghetti G., Campagnolo A., Rigon D. Multiaxial fatigue strength assessment of welded joints using the Peak Stress Method – Part I: Approach and application to aluminium joints. Int J Fatigue 2017; 101:328-342.

[17] Meneghetti G., Campagnolo A., Rigon D. Multiaxial fatigue strength assessment of welded joints using the Peak Stress Method – Part II: Application to structural steel joints. Int J Fatigue 2017; 101:343-362.

[18] Meneghetti G, Campagnolo A. Rapid estimation of notch stress intensity factor in 3D large-scale welded structures using the peak stress method. MATEC Web of Conferences 165, 17004, 2018.

[19] UNI EN 13001-3-1. Cranes – General Design – Part 3-1: Limit States and proof competence of steel structure.