Analysis of methodologies for fatigue calculation for railway bogie frames.

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Abstract

The paper is focused on a critical analysis of the railway bogie frame fatigue strength assessment procedure, with special attention paid to welded joints. Different welded joints fatigue analysis techniques were critically analyzed including also the two different approaches (endurance limit and Goodman diagram) for calculation methodologies proposed in the European standard EN 13749. The aim of the analysis is to understand those which appeared more suitable for bogie frame analysis, taking account of accuracy and applicability. The selected criteria, making use of a purposely developed post-processor for a commercial Finite Element program (ANSYS) were critically compared for reliability and safety. In the paper fatigue analysis is investigated, paying attention on the techniques to adopt for the application of the Finite Element Methods.

Introduction

As a consequence of the standardization process developing in Europe, on April 2005 the new European standard EN 13749 was issued by the European standardization body CEN. The aim of the norm is to define the complete design process of railway bogies. It includes design procedures, assessment methods, verification and manufacturing quality requirements.
The EN13749 norm codifies static and fatigue load assumptions, as well as calculations and test methods to verify the static and fatigue resistance of the bogie frames. In particular for fatigue calculation an important number of load cases is defined in the norm according with the mission profile of the bogie frame (categories of bogies) and the different typologies of forces acting on the bogie frame.
With the improving of new numerical calculation codes (Finite Element Method) the fatigue integrity evaluation has reached high levels especially for the accuracy and for the details of the simulation.
Even the reached improvement some important points remain open and are not yet defined in the norm. The items which will require research work are mainly two. The first one is the method to use for the FEM simulation and the fatigue assessment in the welded joints. The second item is the definition of a standard calculation methodology for the evaluation of the fatigue strength in case of multi-axial stresses (typical for railway applications).
As direct consequence of the above open points the same bogie design can be analyzed for fatigue integrity making use of alternative methods/methodologies potentially giving different results.
Since 2006 the Engineering Department of Trenitalia, the Italian state-owned operator, and the Mechanical Engineering Department of Pisa University are developing a common research project in the field of bogie frames fatigue behaviour. The main aim of this project is to contribute to the set-up of a validated methodology applicable for fatigue integrity evaluation of railway frames through the use of Finite Element simulations.
Concerning Fatigue Strength analysis techniques the main approaches selected and cross-checked are the following:

- "Nominal stress" method
- "Hot spot stress" method
- "Effective Notch Stress" method

For each of the previous methods investigations about the building of the model for FEM analysis were carried out in order to optimize the fatigue calculation of structural components consistent with railway applications. Particular attention was focused on the schematization of the welded joint and the geometric details in relation with the adopted mesh and element types

(shell or brick elements). In this case the aim of the research is oriented to define the more appropriate correlation between FEM schematization and utilized method of analysis.
Regarding the methodologies applicable for fatigue integrity the most important characteristics, advantages or disadvantages connected to the use of the two different approaches proposed in the ERRI B12 RP60 report for fatigue calculations (Goodman diagram and Cumulative damage) has been investigated.
For this goal different post-processors compatible with the FEM software Ansys (used within Trenitalia Engineering Department) has been developed in order to apply the methodologies for fatigue calculation. Three different methodologies have been selected for the implementation of post-processors: the first one according with ERRI B12 RP60 and two others between those analyzed in the first part of the project.
In the final step of the project (within may 2007) the final validation of the calculation model will be carried out through on bench tests. Some structural components and specific samples will be tested in appropriate test rigs (capable of generating multi-axial stress states) in order to determine the fatigue limit of the critic parts (welded joints for example) and to measure the stresses in some main location.
The comparison between the results numerically and experimentally achieved will be used to validate del calculation model.

Fatigue calculation according with EN 13749 for bogie structures

General methodology

As regards the calculation process, the structural analysis is divided in two phases:

- structural analysis of the bogie frame by FEM calculations;
- structural analysis of the attachments components-bogie frame by FEM calculations.

For the two verifications above the calculation process for the acceptance procedure requires the following activities:

- determination of the forces that occur in the interfaces of the structure
- combination of these forces in load cases representing operation conditions
- analysis of the stress values caused by the application of every load cases
- assessment of the calculated stress values comparing them to the acceptable stress limits.

Bogie frame calculation

During bogie lifetime several external forces act in the normal service loads on the bogie frame. These forces are coming from the wheel-rail contact points and from the interfaces with the carbody and are generated from:

- double sprung masses, including payload;
- track irregularities;
- lateral accelerations caused by curve riding;
- longitudinal accelerations caused by traction and braking;

Taking into account all the above listed sources the norm defines formulas and coefficients to evaluate the values of the single forces to apply in the calculation process. Groups of these forces, combined in load cases, allow to simulate the majority of fatigue stress condition on the bogie frame when it is operated on the reference vehicle.
The forces to apply for fatigue calculation are:

- *vertical forces coming from sprung masses*
  According the norm three components are present in these forces:
  - a static component coming from the sprung masses (with normal service payload);
  - a quasi-static component taking account the carbody rolling motion in curve riding; its amplitude is conventionally calculated as a percentage of the static component (roll coefficient α);
  - a dynamic component connected to carbody vertical acceleration in curve riding; its amplitude is conventionally calculated as a percentage of the static component (by means of a bounce coefficient β);

- *transversal forces coming from each axle*
  For all bogie categories the transversal forces are the inertial forces caused by curve riding and by track defects. According to the norm two components are present in these forces:
  - a quasi static component equal to 0.063 g due to non compensated acceleration;
  - a dynamic component equal to 0.063 g due to track irregularities.
- *longitudinal forces:*
  Longitudinal forces are caused from sliding between wheel and rail connected with yaw motion on straight track and with the radius difference of the rolling circle on curves.
- *track twist*
  A conventional track twist 0,5% shall be calculated in order to take into account the effects of typical twists of bogie in curve transitions.

An example of load combinations for passenger and locomotive applications is shown in figure 1. In this case vertical, transversal and track twist forces have to be combined on 9 load cases. Moreover, the norm defines other two load cases adding longitudinal forces to vertical forces. According the norm, these load cases take into account all the possible load configurations in normal operations.
The fatigue calculation requires the evaluation of stresses for every load cases and the analysis of the fatigue cycle characteristics on all the bogie frame in order to check the fatigue resistance. The two different approaches proposed by the norm with their benefits and disadvantages are described below.

- *Endurance limit*
  It's the method mainly used utilized since the issuing of UIC leaflets and it is used also for the analysis of fatigue static tests (afterwards described). In this method the maximum and minimum stress values σ_{max} and σ_{min} generated by the all load cases separately applied are determined on each point of the bogie frame. These values allow to define the mean stress σ_m and the fatigue cycle amplitude to compare with the fatigue limit of the material (using for example the Goodman diagram).
  This method is generally conservative and does not require the knowledge of load spectrums applied on the bogie in its lifetime. A major advantage of the method is that the fatigue limits for the typical steels used for bogies are very well known for the basic material as well as for the majority of welded joints, also in case of not heat treated bogies (the report ERRI B12 RP 60 gives all the fatigue data and the Goodman diagrams). A disadvantage of the method is the rough simplification carried out on the real load spectrum applied on the bogie.
- *Cumulative damage*
  According to this method all the effects due to the combinations of load cases are considered. The estimated number of cycles applied on the bogie for each load cases is the data which is necessary to know and which is used to verify the fatigue resistance by means of the Wohler diagram (S-N) of the material. Then, in agreement with a hypothesis for damage accumulation (for example Palmgren-Miner rule), the total damage can be determined.
  The use of load spectra close to reality is the main advantages of the method allowing to optimize structural strength and weight of the bogie frame. At the same time the definition an load spectrum taking into account all the operative condition is a very complex item to perform.

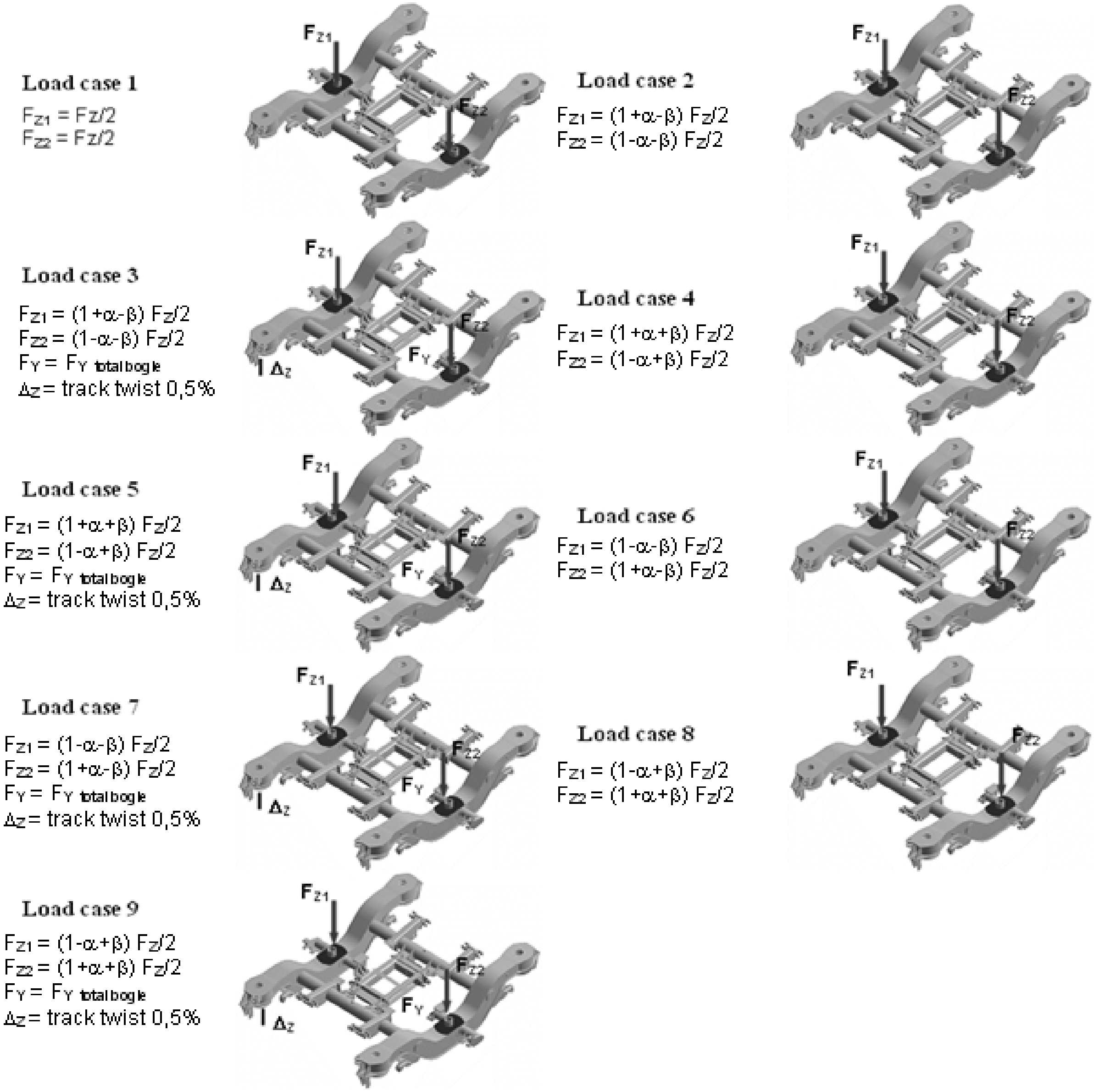


Figure 2 – Load cases for fatigue calculation of passenger and locomotive bogie frames

Frame attachments calculation

During bogie lifetime both operative and inertial loads act on the attachments to the bogie frame. For the fatigue calculation with normal service loads the forces are applied taking into account the typical parameters introduced by the components attached to the frame:

- inertial forces due to the masses attached to the bogie frame;
- inertial forces due to the masses attached to the axle box (unsprung masses);
- loads resulting from damper
- loads resulting from braking;
- loads resulting from traction motor;
- load applied on anti-roll system;

The fatigue calculation shall be carried out separately for every support. Two load cases for each calculation have to be performed:

– vertical loads (due to sprung masses) and maximum/minimum inertial service accelerations acting on the attachments;
– vertical load (due to sprung masses) and maximum/minimum operative forces acting on the attachments (due to dampers, braking, etc.).

The verification methods are the same described for the fatigue calculation of the bogie frame.

Relevant factors for Fatigue Strength analysis

The fatigue behaviour of welded structures is significantly affected by few factors (Fig. 2), which are specific for these structures or assume for them a quite higher relevance, as compared to other typically fatigue loaded structures.
The most important among these factors [3-5, 9, 10] are:

- stress concentrations;
- material mechanical properties variation between different weld joint zones;
- residual stresses;
- fatigue cycle mean stress;
- presence of defects (cracks)

In addition, a few other factor, such as:

- stress multi-axiality
- variable amplitude loading

assume a specific relevance in connection with railway structures.
All of these factors need to be adequately accounted for in an analysis tool to be employed for railway bogies fatigue strength assessment.
In the following, the effects of some of these factors will be briefly analysed.
Stress concentrations in welded structures are mainly due to the following two mechanisms:

- weld joint geometry
- material properties variation within the joint

Among these, the weld joint geometry is generally the most important, as weld joint cross shape usually includes quite abrupt shape variations, with very small root radius values. The theoretical stress concentration factor ($K_t = \sigma_{max}/\sigma_{nom}$) due to geometric effects typically assumes values ranging from 1.5 up to 5 [6-7]. On the contrary, the stress concentration

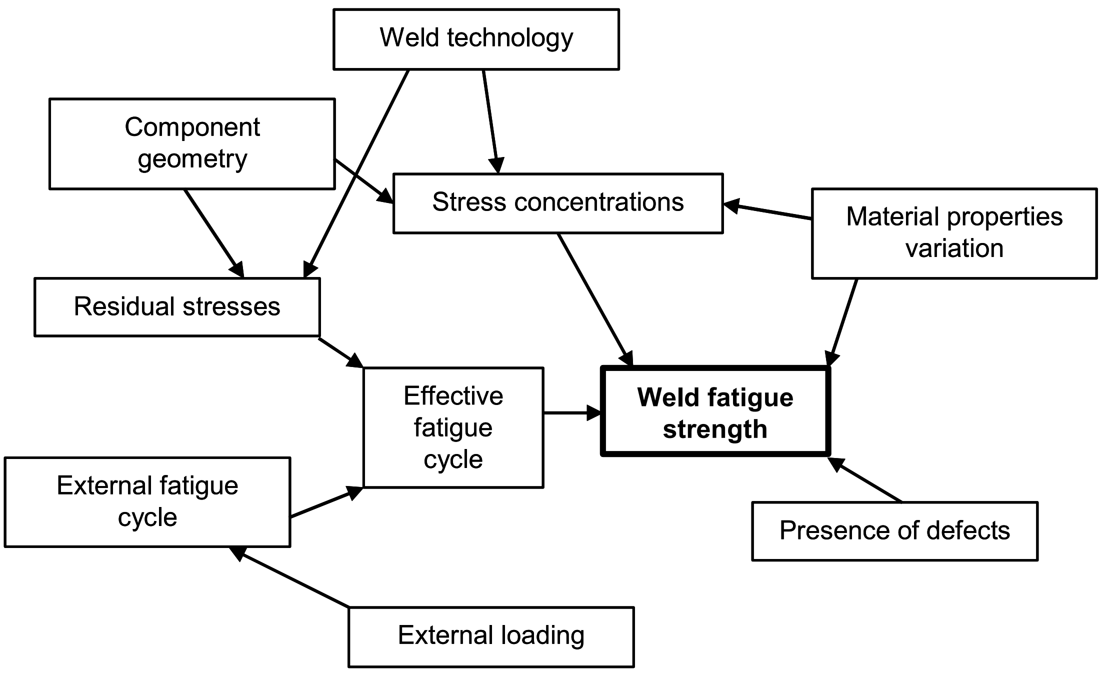


Fig. 2 – Factors affecting welded structures fatigue strength

factors produced by material elastic properties (in particular, Poisson's ratio, ν) variation in different joint regions (i.e. Base Material (BM), Heat Affected Zone (HAZ) and Fusion Zone (FZ)) are rather small, usually not exceeding 1.1-1.2.
A specific problem with welds is that geometric notch root radius are usually very small (typically, less than a few tenth of millimetre). Therefore, elastic maximum stress cannot be employed to predict fatigue life, but it must be replaced by a "effective" value, accounting for notch sensitivity.
Actual K_t values for welded joints can, in principle, be efficiently evaluated by Finite Element (FEM) models. However, uncertainties in actual joint geometry (which, moreover, usually varies along the weld) can make this evaluation rather difficulty and specific analysis procedures were developed.
Material fatigue strength variation within the joint should, in principle jointly act with stress variation to determine the actual fatigue failure initiation site. In practice, however, the former effect is overridden by the latter and fatigue failure is usually observed to occur in one of the highest stress concentration position, i.e. the weld root or the weld toe.
Residual stresses in welded structures can reach quite high values, depending on structure geometry and static indeterminacy degree and on the welding technology (type of welding, welding sequence, etc.). The determination of actual residual stress level, either by means of measurement or through the use of computer (i.e. FEM) simulation of the welding process is a quite complex matter, whose results are often affected by very high uncertainty and variability.
The typical effect (Fig. 3) of residual stresses (σ_{res}) on fatigue behaviour of structures is that of superimposing to stresses due to external loading (σ_{ext}), increasing the cycle mean stress (σ_m). An increase of σ_m is usually accompanied by a reduction of fatigue life and this is also the case for welded structures, at least in the presence of rather small residual stresses (e.g. in structures subjected to Post Weld Heat Treatment (PWHT)).

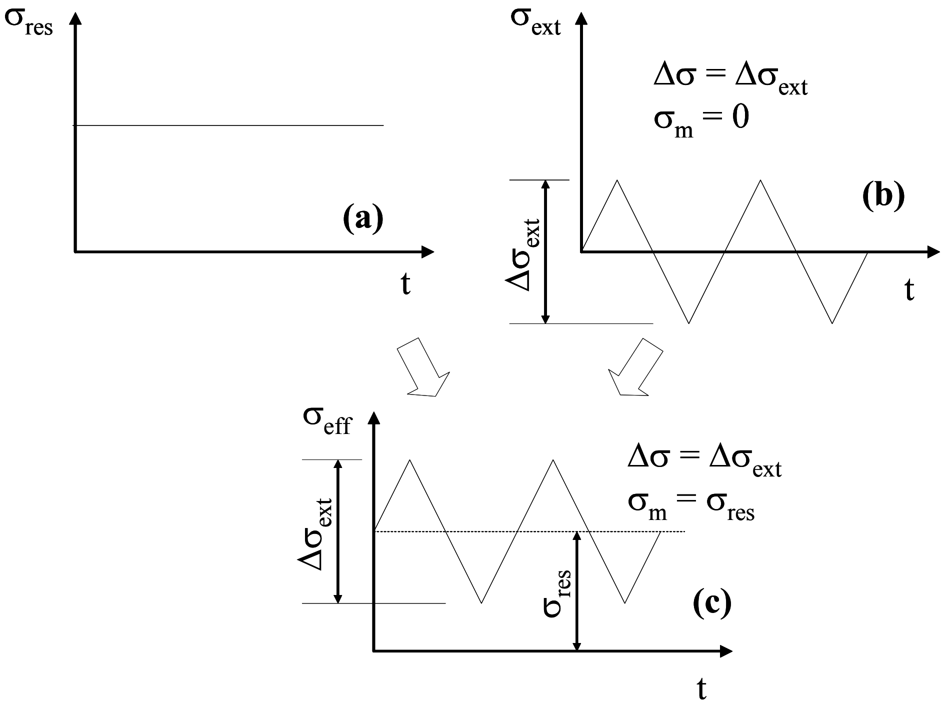


Fig. 3 – Residual stress effects on fatigue cycle: (a) residual stress, (b) fatigue cycle due to external loading, (c) effective fatigue cycle.

However, if the maximum stress in cycle exceeds material yield strength (which is usually the case for rather high residual stresses, as in structures not subjected to PWHT) it is substantially upper limited to such value and, as a consequence, the cycle mean stress become rather

independent from external cycle mean stress always attaining the minimum value, typical of very high stress values [6].
The effects of residual stresses are usually not directly accounted for in fatigue life evaluation. Structures are usually classified into different categories, typically expected to be affected by high or low residual stresses, each with specific allowable stress limits.
The presence of crack like defects, rather common in welded joints can highly reduce fatigue strength, actually reducing to zero or near zero values the number of cycles required for initiation. Defects are usually dealt with in regulations trough acceptability limits, under which their effect on fatigue life can be considered negligible [1].

Fatigue Strength analysis techniques

Several examples of welded fatigue analysis techniques can be found in the technical literature, which mainly differ each other as regards the detail in required stress analysis and the generality of application field. In addition, several purposely developed analysis methods were developed for specific application fields (e.g. cranes, buildings, pressure vessels, offshore structures).
Among the most widely applied general purpose analysis techniques, one can surely include:

- "Nominal stress" (NS) method [1, 2]
- "Hot spot stress" (HSS) method [1, 8]
- "Effective Notch Stress" (ENS) method [9]

In addition, the EN13749 standard, purposely fitted for bogies and railway structures fatigue analysis, was considered in the present work.
Nominal stress method is based on the definition of a conventional weld section and on the use of simple beam theory models to derive stress distributions (constant or linear) which can guarantee equilibrium to external forces and moments that the welded joint is required to transfer. Stress evaluation by this technique is quite simple and can often be conducted manually or by quite simple FEM models. As a shortcoming, we must observe that, as the ratio between actual maximum stress and nominal stress acting in the joint is clearly affected by:

- local weld geometry
- global geometry of the joint
- type of loading (e.g. normal stress, bending, etc.)

a specific fatigue strength curve is required for each combination of the above parameters and, as a consequence, a lot of different fatigue curves are required and this cannot ensure to find the suitable one for a specific application case. In the following, the application of the nominal stress method will be based on the EUROCODE strength curves [1].

The "hot spot" method, firstly developed for offshore platforms structural analysis, is based on recognizing that the stress distribution near a welded joint has two main contributions (Fig. 4):

- a linear through the thickness distribution, equilibrating external loads ("geometric" stress), whose maximum value at the weld toe is called "hot spot" stress (σ_{HS});
- a non-linear distribution, having zero force and moment resultant, representing local perturbation due to weld notch geometry ("peak" stress)

The basic idea of the HSS method is that the maximum actual stress acting at the weld toe will be proportional to the "hot spot" stress, by a factor which will only depend on the weld local geometry (and not on the global joint geometry). Therefore, a fatigue strength curve is required for each weld geometry only (e.g. butt or fillet welds), so greatly simplifying and rationalizing the analysis. The main shortcoming of the method can be recognized in the theoretical and practical difficulties connected with "the "hot spot" stress evaluation. Indeed, the stress field calculated via any FEM model will necessarily show both the linear stress contribution and an approximated estimate of the non linear contribution. So, in order to determine the linear contribution only, special extrapolation techniques (for which are necessary particular mesh construction criteria) are required. Another shortcoming of the HSS method is the weld toe failure only is considered, excluding the possibility of a failure at the weld root.

The Effective Notch Stress method is based on the evaluation of an estimate of the actual maximum stress acting in the joint, at the weld root or toe (Fig. 4)

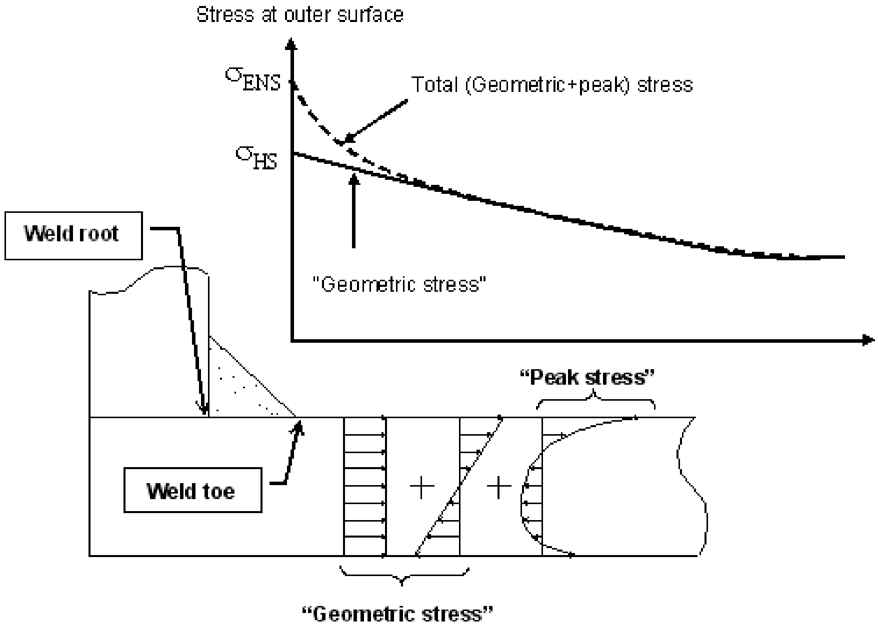


Fig. 4 – Stress contributions in welded joints, with "Hot Spot" Stress and "Effective Notch Stress" indication

As it can easily recognized that:

- maximum notch stress is highly affected by local weld geometry which, moreover, is usually highly variable along the joint
- weld notch root radius is usually very small and, therefore, linear elastic maximum notch stress value cannot be assumed as the controlling factor for fatigue failure

an "effective" fatigue notch stress is assumed. This can be seen as an average stress over a micro-structurally controlled characteristic region beyond the notch root and can be effectively calculated by replacing the (variable and unknown) actual notch root radius with a conventional (constant) one, depending on material only (e.g. for structural steel, a t 1.0 mm value is typically assumed). An example of FEM model for ENS evaluation is shown in Fig. 5. As highly refined meshes are usually employed, the substructure analysis technique is advantageously employed.

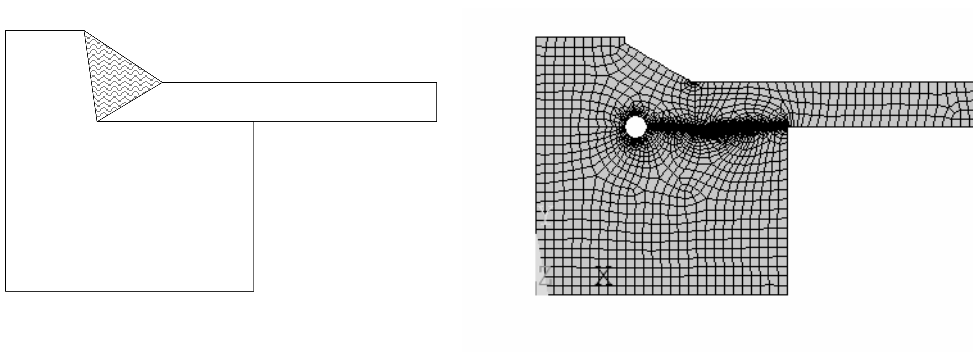


Fig. 5 – Example of FEM mesh with effective notch root radii for ENS evaluation

In this case, the fatigue strength curve can be unique for the given welding technology. The main shortcoming of the ENS method is the complexity of the analysis and difficulties in applying to situations where the effective notch radius is comparable with actual steel sheet thickness (the method is qualified for welded sheets whose thickness exceeds 5-6 mm). As regards the effects of multi-axiality, empirical relationships are usually employed with the nominal stress method, while the maximum principal stress criterion is the most widely employed together with the HSS and the ENS methods.
The ERRI B12/RP60 code for fatigue analysis of railway bogies indicates two alternative fatigue analysis techniques:

- Cumulative Damage Method (CDM)
- Goodman Diagram Method (GDM)

These techniques are ideally based on the experimental determination of representative stresses acting in the structure, by strain gauges. The measurement can, however, be easilly substituted by a FEM simulation, so transforming the experimental method in a numerical one, which can be employed at least in the design stage.
The CDM is essentially aimed at an approximate evaluation of the nominal stress. The strain gauge is located at some distance from the weld toe (30% of the sheet thickness, usually 8-10 mm for railway bogies), so avoiding local stress concentrations due to weld geometry and allowing an approximated estimate of the nominal stress to be obtained. The multi-axiality criterion is essentially the maximum principal stress one, while fatigue strength curves (similar to those reported in [1]) are given for a series of weld geometries, typically encountered in bogies.
On the contrary, the GDM is aimed at an approximate evaluation of the HSS. This is obtained by locating the strain gauge quite closer to the weld joint, as compared to the CDM. In this case also, the maximum principal stress criterion is employed to account for multi-axiality. Specific Goodman's diagrams are given for different weld technology (e.g. butt or angle welds).

FEM fatigue analysis of welded joints

The criteria to be employed for the development of a suitable and accurate FEM model to support the structural and fatigue analysis of a bogie welded frame are highly dependent on the selected fatigue analysis method.
Indeed, the stress estimates required by the previously discussed analysis techniques are quite different each other and the FEM model must take proper account of the requirements for their evaluation.

Nominal stress method

The FEM model can be constructed both employing solid ("brick") elements or "shell" elements. In both cases, it is important to have a correct simulation of effective welded joint stiffness, as compared to base metal sheet stiffness, as this can affect stress distribution within the different regions of the joint.
For fillet welds, this makes it preferable to schematically represent the weld transverse geometry (Fig. 6) and, in the case of shell models, to insert specific elements having a conventional representative thickness.
Of special concern is the mesh size in the weld zone. Indeed, an excessively coarse mesh could not be able to estimate required stress with acceptable accuracy, while a too refined mesh could evidence undesired or spurious effects, such as stress singularities.
The nominal stress can usefully be calculated by extracting the forces and moments transmitted through a weld length of the order of the transverse size and calculating, by simple beam theory relationships, the stresses produced on the corresponding resistant section.

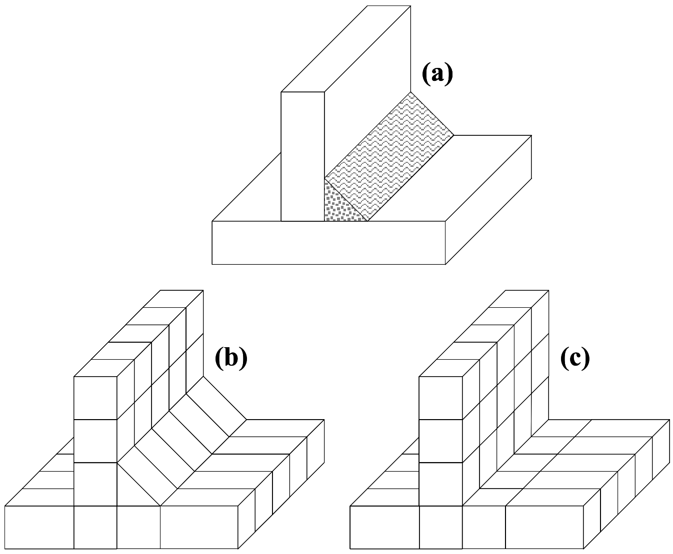
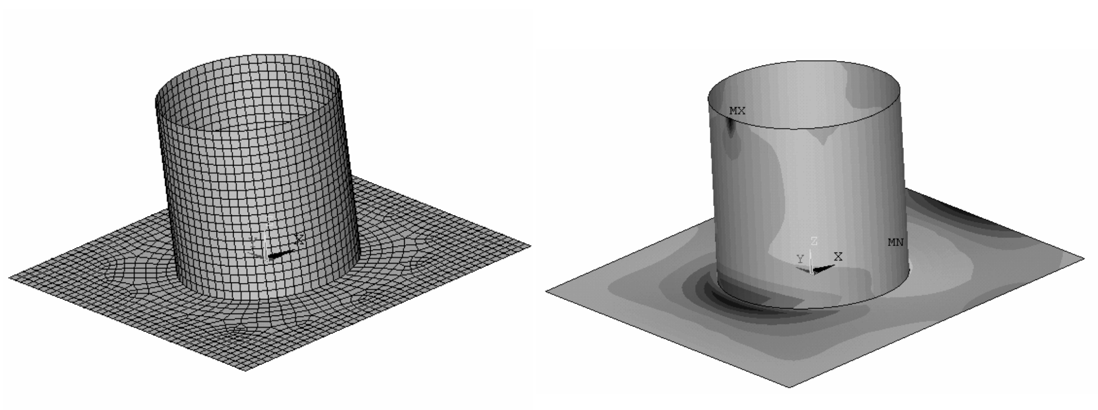


Fig. 6 – FEM analysis (“brick” elements) of fillet welds: a) joint geometry; (b) FEM model, including schematic weld representation; (c) FEM model without weld representation

“Hot spot” stress method

The HSS requires an estimate of the linear component of the stress filed at the weld toe. This stress component is best achievable by “shell” element models (Fig. 7), which automatically filter the non-linear component. In the years, several modelling techniques have been developed imposing specific element sizes in front of the weld, to improve HSS evaluation accuracy. This tend to make FEM model set-up quite laborious.



(a) (b)

Fig. 7 – FEM analysis (“shell” elements) of a tubular welded joint, typically employed for HSS evaluation

“Effective Notch Stress” method

The FEM model for ENS evaluation is most frequently based on sub structuring techniques (Fig. 8). A coarse model, similar to those suitable for nominal stress method, is employed to represent general structure displacement field. Then a substructure representing the weld detail and including effective notch root radius is employed to derive ENS.

One of the most interesting potentialities of the method is the possibility to account, at least in principle, of effects such as weld shape defects, including them in the substructure.

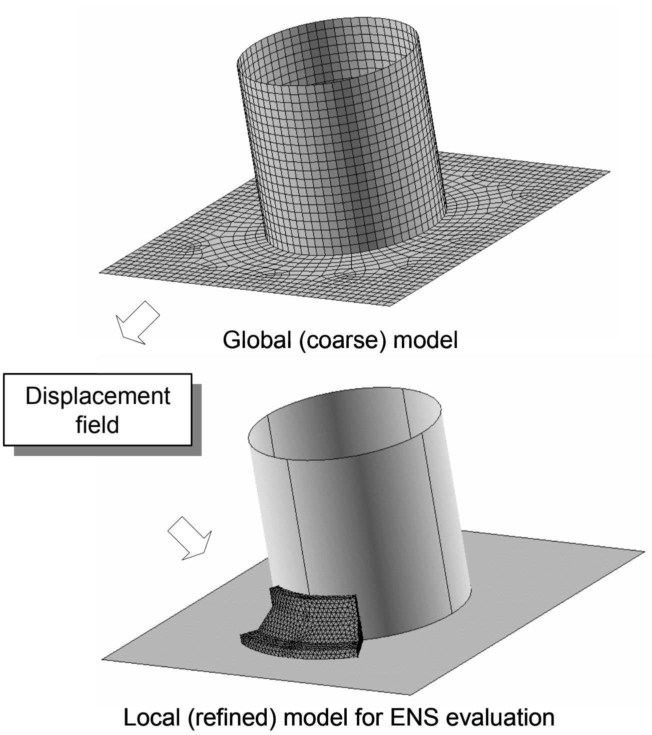


Fig. 8 – Typical FEM model for ENS evaluation, based on a sub structuring technique

Application to fatigue analysis of bogie frames

The previously outlined fatigue life calculation methods were applied on some design of bogie frame used in Trenitalia application and representing quite different categories.
An example of FEM model employed for bogies analysis is reported in Fig. 9.
For the main selected calculation methodology a post-processor compatible with the FEM software Ansys has been developed in order to obtain fatigue calculations and to compare the achieved results.
Based on such applications, the following main observations can be drawn:

- Nominal stress, based on EUROFER code and ERRI B12/RP60 CDM produced rather comparable results, which is not surprising, taking account of the analogies between the two techniques
- HSS, ERRI B12/RP60 GDM and ENS techniques produced rather comparable results, with predictions less conservative than NSM and ERRI B12/RP60 CDM. The application of HSS and ENS techniques appeared quite more complicated, as compared to the other methods, from an user point of view, mainly due to the rather strict requirements on FEM model and to sensitivity to mesh details
- as the actual fatigue strength of the bogies was not known, it was not possible to draw sound conclusions about the accuracy of the different methods predictions.

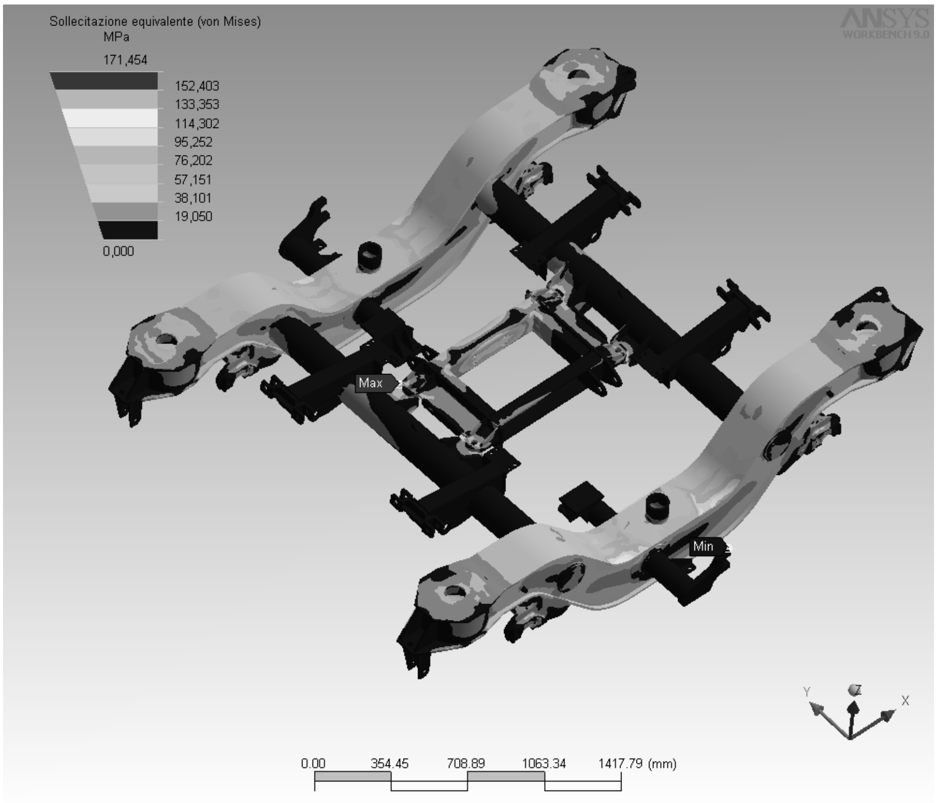


Fig. 9 – Example of FEM model for railway bogie fatigue analysis

Conclusions and future work

Based on above mentioned results, the following main conclusions can be drawn:

- a critical analysis of a few quite popular welded structure fatigue analysis techniques was conducted, discussing theoretical basis and application potentialities
- in addition, the ERRI B12/RP60 code was also analysed
- the FEM model requirements for the application of the considered analysis techniques were also discussed, indicating a few critical points
- the "Hot Spot" Stress method, the Effective Notch Stress method and the ERRI B12/RP60 Goodman Diagram Method produced comparable results, with predictions less conservative as compared to the Nominal Stress Method and to the ERRI B12/RP60 Cumulative Damage Method
- it was not possible to draw definitive conclusion about the accuracy of the methods, as actual fatigue failure data for the bogies were not available

In the final part of the project, the execution of full scale tests on structural parts of the bogies (within may 2007) will permit to achieve specific experimental S-N curves to compare with model predictions. This will be very important for the validation of the selected method and calculation methodology.

The achieved results and the experience developed in the projects should be useful for the future revision of the norm EN 13749 in order to complete the acceptance procedure of the bogie frame design.

References

[1] EN 1993: (Eurocode 3) Design of steel structures

[2] W. Fricke, A. Muller-Schmerl, "Uncertainty Modeling far Fatigue Strength Assessment of Welded Structures", ASME Joumal of Offshore Mechanics and Arctic Engineering, MAY 1998, vol. 120, pp. 97-102.

[3] J. L. Hechmer, E. J. Kuhn, III, "Fatigue Strength Reduction Factors for Welds Based on Nondestructive Examination", *ASME J. of Pressure Vessel Technology*, 1999, vol. 121, pp. 6-10

[4] Carl E. Jaske, "Fatigue Strength Reduction Factors for Welds in Pressure Vessels and Piping", *Journal of Pressure Vessel Technology,* ASME, 2000, Vol. 122, pp. 297-304

[5] K.J. Kirkhope, R. Bell, L, Caron, R.I. Basu, K.-T. Ma., "Weld detail fatigue life improvement techniques. Part 1: review", *Marine Structures,* vol. 12 (1999) pp. 447-474

[6] N.T. Nguyen and M.A. Wahab, "The effect of undercut, misalignment and residual stresses on the fatigue behaviour of butt welded joints", *Fatigue Fract. Engng Mater & Struct.,* Vol. 19, No.6, pp. 769-778, 1996

[7] D. Radaj, "Fatigue notch factor of gaps in welded joints reconsidered", *Engìneerìng Fracture Mechanìcs*, Vol 57, No 4, pp 405-407, 1997

[8] G. Savaidis, M. Vormwald, "Hot-spot stress evaluation of fatigue in welded structural connections supported by finite element analysis", Intemational Joumal of Fatigue, vol. 22 (2000) pp. 85-91

[9] C.M. Sonsino, D. Radaj, U. Brandt, H.P. Lehrke, "Fatigue assessment of welded joints in AIMg 4.5Mn aluminium alloy (AA 5083) by local approaches", *Intemational Joumal or Fatigue,* vol. 21 (1999) pp. 985-999.

[10] Y. Verreman and B. Nie, "Early development of fatigue cracking at manual fillet welds", *Fatigue Fract. Engng Mater & Struct.,* Voi. 19, No.6, pp. 669-681, 1996