Cumulative damage assessment in structural steel details

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Appréciation des dommages cumulatifs sur des détails de structures métalliques

Beurteilung kumulativer Schäden in Stahlbaukonstruktionsdetails

Carlo A. CASTIGLIONI
Associate Professor
Polytechnic of Milan
Milan, Italy

Carlo A. Castiglioni, born in 1956, is Associate Professor in the Structural Engineering Dept at the Polytechnic of Milan. After receiving his civil engineering degree from the Polytechnic of Milan in 1980, he was on the Visiting Faculty at Lehigh University, Bethlehem, PA, USA, in 1984. His main research fields are high and low cycle fatigue of steel structures.

SUMMARY

An approach is presented trying to unify both design and damage assessment methods for high and low cycle fatigue, based on the results of an extensive experimental research programme. Interpreting the stress range in a structural component as the one associated to the real strain range in an ideal perfectly elastic material, high and low cycle fatigue test data can be fitted by the same Whöler lines usually given in recommendations for the fatigue design of steel structures. Local buckling can be regarded as a notch effect, intrinsic to the various shapes, and related to their geometrical properties.

RÉSUMÉ

A partir d'un programme exhaustif de recherche expérimentale, l'auteur essaie de combiner entre elles des méthodes d'étude et des procédés d'appréciation des dommages provoqués par la fatigue résultant de cycles alternés de charges faibles et fortes. Étant donné que l'amplitude de la sollicitation d'un élément structural peut être saisie à partir de l'amplitude de l'allongement réel d'un matériau idéalement élastique, il est possible de représenter les données de fatigue de ces cycles de charges alternées par les mêmes lignes de Whöler, telles qu'elles sont habituellement recommandées pour le dimensionne-ment à la fatigue des constructions métalliques. Par ailleurs, un voilement local peut être considéré comme résultant de l'effet d'une concentration de contraintes, spécifique aux différentes sections et aux propriétés géométriques.

ZUSAMMENFASSUNG

Auf der Grundlage eines umfangreichen experimentellen Forschungsprogramms wird versucht, Entwurfsmethoden und Verfahren zur Schadensbeurteilung für Ermüdung unter hohen und niedrigen Lastwechselzahlen miteinander zu kombinieren. Indem die Spannungsamplitude in einem Bauteil als reale Dehnungsamplitude in einem idealelastischen Werkstoff aufgefasst wird, können die Ermüdungsdaten für hohe und niedrige Lastwechselzahlen durch dieselben Whölerlinien repräsentiert werden, wie sie üblicherweise für die Ermüdungsbemessung von Stahlkonstruktionen empfohlen sind. Oertliches Beulen kann als Kerbeneinfluss, spezifisch für die unterschiedlichen Formen und geometrischen Eigenschaften, aufgefasst werden.

1. INTRODUCTION

Eurocode-3 [1] defines fatigue as "damage in a structural part, through gradual crack propagation caused by repeated stress fluctuations". Depending on a number of factors, these load excursions may be introduced either under stress or strain controlled conditions. Depending on the number of cycles sustainable to failure, and on their amplitude, we can distinguish failure for high or low cycle fatigue.
Failure by high cycle fatigue is characterised by a large number of withstandable cycles with a nominal stress range $\Delta\sigma$ in the elastic range. This is a well known effect [2], although only a limited number of typologies of connections and of structural details can be considered at present thoroughly investigated, and general aspects of this problem and the basic methodologies for assessment and design, can be considered well established.
Low cycle fatigue is characterised by a small number of cycles to failure, with large plastic deformations. In general, low cycle fatigue problems in civil engineering structures arise either under seismic loading or in pressure vessels or under severe thermal cycling. Cycles with large amplitudes in the plastic range are usually connected with local buckling in structural members. At present, knowledge of low cycle fatigue behavior of civil engineering connections is not jet as well established as high cycle fatigue one; in particular there is no generally recognised design or damage assessment method, and a clear definition of a collapse criterion is lacking.
In this paper a procedure is described, trying to unify design and damage assessment methods for structural details under high and low cycle fatigue. After discussing the proposed approach, its experimental validation based on constant and variable amplitude cyclic test results will be presented. By transforming the nominal strain range $\Delta\varepsilon$ in an equivalent stress range ($\Delta\sigma^*=\Delta\varepsilon\ E$) computed by considering the material as indefinitely linear elastic, the experimental test data obtained under cycles with a constant amplitude in the plastic range can be interpolated by the same Stress range-Number of cycles to failure (S-N) lines usually given in recommendations for the (fatigue) design of steel structures (e.g. [1]). Furthermore, a linear damage accumulation model [16] (Miner's rule), together with the rainflow cycle counting method, can be adopted for the damage assessment under variable amplitude loading.

2. THE PROPOSED APPROACH

The proposed approach to unify design and damage assessment procedures for steel structures under low and/or high cycle fatigue, extensively discussed in [3], is based on the two following assumptions:

1. To know, for a given structural detail (cycled under strain controlled conditions), the relationships between the number of cycles to failure N_f and the cycle amplitude Δs, expressed in terms of generalised displacement components (i.e. of displacements Δv or of rotation $\Delta\phi$ or of deformation $\Delta\varepsilon$). These relationships have the same meaning in high and low cycle fatigue with the following difference:
   - in high cycle fatigue the component is subjected to cycles in the elastic range;
   - in low cycle fatigue the component is subjected to cycles in the plastic range .
2. Damage accumulation in a structural detail is a linear function of the number of cycles sustained by the component itself. This means that Miner's rule [16], can be applied also in low cycle fatigue.

Consequence of the second assumption is the definition of a unified failure criterion for both high and low cycle fatigue; of course appropriate S-N curves corresponding to the desired safety level should be identified. Consequence of the first assumption is the possibility to interpret low cycle fatigue with the same laws commonly accepted for high cycle fatigue. In fact, in high cycle fatigue (under stress controlled conditions) a structural component is subjected to load cycles having a constant amplitude $\Delta\ F<F_y$ (the yield strength, theoretically computed or experimentally evaluated) and the nominal stress range induced by the external load $\Delta\sigma=\Delta\sigma(\Delta F)$ (computed either theoretically or with conventional methods) is correlated to N_f, independently from the yield strength of the material.
In order to generalise this approach, for an indefinitely linear elastic material, it can be written:

$$\Delta\sigma = \frac{\Delta F}{F_y}\sigma(F_y) \qquad (1)$$

In low cycle fatigue (under strain controlled conditions), a structural component is subjected to displacement cycles having a constant amplitude $\Delta\ s<s_y$ (associated with the attainment of the yield stress in the material, that may be theoretically computed or experimentally evaluated). If the material can be regarded

as an elastic perfectly plastic one (as in the case of steel), and the hypothesis of concentrated plastic hinge can be considered realistic (as for steel members under seismic loading [4]), it can conventionally be assumed that strains are proportional to the generalised displacement component *s*, and it can be stated that:

$$\frac{\Delta\varepsilon}{\varepsilon_y} = \frac{\Delta s}{s_y} \qquad (2)$$

As discussed in [3], equation (2) defines the nominal strain range in a particular way [3], taking into account the local reduction of stiffness at plastic hinge location by an equivalent uniform stiffness reduction along the total beam length, and can be rewritten as follows:

$$\Delta\sigma^* = E\Delta\varepsilon = E\frac{\Delta s}{s_y}\varepsilon_y = \frac{\Delta s}{s_y}\sigma(F_y) \qquad (3)$$

Equation (3) is similar to equation (1), valid for high cycle fatigue.

3. EXPERIMENTAL VALIDATION

3.1 Re-processing the test data

For re-processing test data according to equation (3), the following parameters must be defined: the number of cycles to failure N_f, the values of the generalised displacement component (s_y) and of the stress level corresponding at first yield ($\sigma(F_y)$).
To define N_f, a collapse criterion must be adopted, either assumed conventionally a-priori [4,7-9], or identified test by test corresponding to failure. The value of the generalised displacement component corresponding to first yield can be theoretically computed or conventionally defined, for example reprocessing test data according to ECCS Recommended procedures [6]. The nominal stress level at first yield($\sigma(F_y)$) can be determined either experimentally by tensile tests, or theoretically. In the second case, both F_y and, for flexural members, the dimension of the plastic hinge should be defined.
Once determined N_f, test data can be re-processed to plot in a log-log scale N_f vs. $\Delta\sigma^*$ given by eq. (3). The domain *log* ($\Delta\sigma^*=E\Delta\varepsilon$) *vs. log N* is the usual domain for the S-N curves adopted by various International Codes for (high cycle) fatigue design of steel structures. In order to verify the assumption of equivalence of $E\Delta\varepsilon$ - N_f curves for high and low cycle fatigue, hereafter it is tried to interpret the experimental test data of low cycle fatigue tests performed on structural steel members and joints, by means of the *S-N* curves proposed by EC-3 [1] extended in the low cycle fatigue range by means of eq. (3).

3.2 Members

3.2.1 Constant amplitude tests

In order to experimentally validate the proposed approach, tests were performed at the Structural Engineering Department of Politecnico di Milano [4], on full scale cantilever members (1.6 m long) of the commercial shapes HE120A, HE140A, HE220A, HE220B and IPE300 using an equipment [5] capable of applying horizontal cyclic actions in a quasi-static way. Presently, the testing programme is continuing, in order to enlarge the data-base and tests are carried out also considering the presence of an axial load [7,8].
To date, 40 tests were performed imposing to the specimens displacement cycles with a constant amplitude (11 on HE220A shapes, 12 on HE220B and 11 on IPE300, 3 on HE120A, 3 on HE140A) . Furthermore, 3 tests on HE120A, and 8 tests on HE220A were performed on specimens, subjected to an axial load. In high cycle fatigue, strength categories implicitly account for different notch effects, i.e. for different local stress concentrations due to geometry of the detail and/or defects caused by fabrication procedures. It is supposed that the same consideration holds also in the case of low cycle fatigue: local buckling can in fact be regarded as a notch effect, because it induces local stress concentrations in the buckled area (at plastic hinge location). In fact, as discussed in [4,7,8] and in good agreement with previous results [10-12], the different geometries of the cross sections make the specimens more or less vulnerable by local buckling

effects. This means that each shape, as a function of its geometrical properties, can be considered as belonging to a definite fatigue strength category, because intrinsically affected by a more or less pronounced notch effect. It must be expected that the different shapes belong to different fatigue strength categories. Figure 1 shows the test data for beam specimens [4] failed by cracking in the base material at plastic hinge locations, fitted by the S-N lines of Eurocode-3. The parameter which seems to govern the fatigue behavior of beams is the d/t_w ratio. In fact, it can be noticed that test data for HE120A specimens (having lowest d/t_w) can be fitted by line for category 90, those for HE220B and HE140A (having similar d/t_w) can be fitted by EC-3 line for category 80, those for HE220A by category 71, while those for IPE300 (having largest d/t_w) by category 63.
The tested specimens evidenced two different failure modes: by cracking in the base material at plastic hinge locations, or by cracking at welding of the reinforcement plates to the specimens. It must be expected that different fatigue strength curves apply to different failure modes.In fact, as shown in fig. 2, HE220A and HE220B specimens can be fitted by category 63 line, while IPE300 specimens, despite the same welded detail was adopted for all shapes, are fitted by line 56 and show a lower fatigue strength[4]. Independently on the fatigue resistance category pertinent to each shape, it is important to notice that the slope of the line fitting (in a log-log plot) the low cycle fatigue test data, reprocessed according to eq. (3), is nearly -3, in good agreement with the results of research on high cycle fatigue.

Fig. 1 Fatigue strength of beams failed at plastic hinge

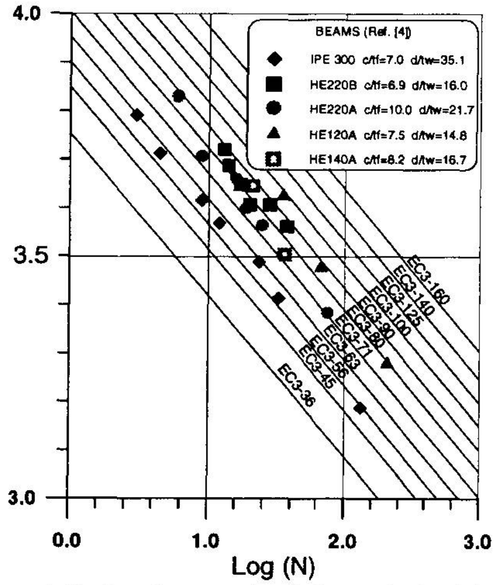


Fig. 2 Fatigue strength of beams failed at weldings [4]

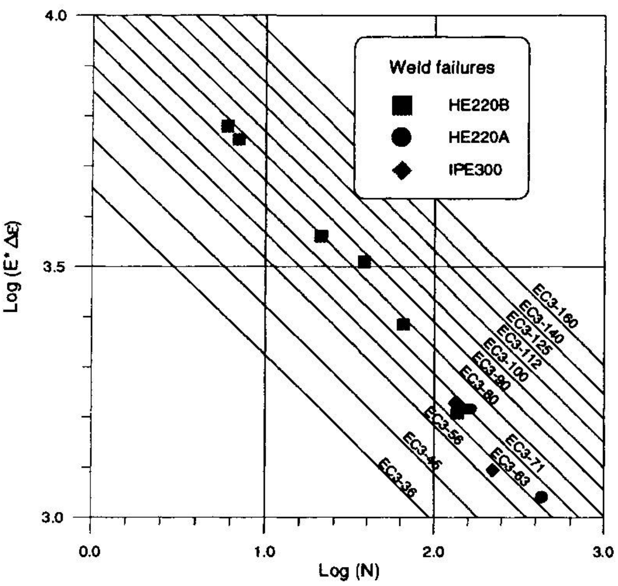


Table 1 - Damage indexes corresponding to specimen collapse in variable amplitude tests

TEST	EC-3 90	EC-3 80	EC-3 71	EC-3 63	Failure
HEA1	0.542	0.772	1.104	1.580	P.H.
HEA9	0.854	1.202	1.740	2.489	P.H.
HEA10	0.599	0.853	1.220	1.746	P.H.
HEA11	0.773	1.040	1.490	2.135	P.H.
HEB1	1.420	2.030	2.900	4.152	P.H.
HEB12	0.717	1.020	1.460	2.090	W
HEB13	0.523	0.744	1.060	1.524	W
IPE9	0.461	0.657	0.939	1.340	P.H.
IPE10	0.385	0.547	0.783	1.120	P.H.
IPE11	0.460	0.660	0.940	1.346	P.H.
IPE15	0.478	0.680	0.973	1.394	P.H.

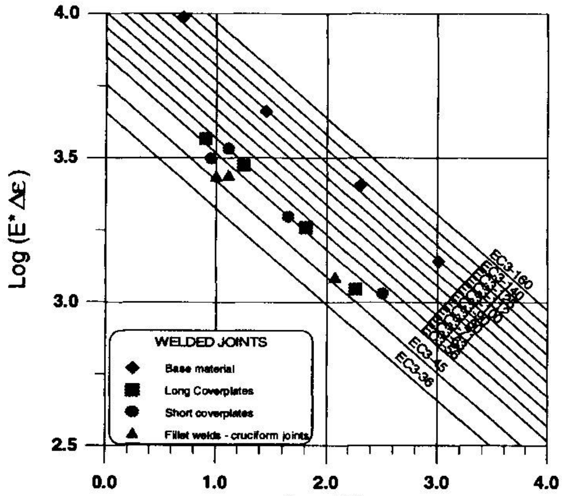
3.2.2 Variable amplitude tests

At present, a total of 11 variable amplitude tests have been performed at Politecnico di Milano [4] (4 on HE220A shapes, 4 on IPE300 and 3 on HE220B). The experimental results were re-processed by means of the rainflow cycle counting method and Miner's damage index [16] associated with collapse of each specimen was computed, based on the transformation given by equation (3) and on the EC-3 fatigue strength lines previously identified for the various profiles. The obtained results are summarised in table 1 where the failure mode (P.H.= at plastic hinge, W= at welding) and the damage index corresponding to the EC-3 lines are given. It can be noticed that Miner's rule [16] gives damage index values with scatters similar to those commonly accepted in random high cycle fatigue, and correctly allows prediction of failure in association with EC-3 line 71 for HE220A specimens and with line 63 for IPE300 specimens. For HEB specimens, depending on the failure mode, a correct prediction of failure is achieved respectively in association with EC-3 fatigue strength lines 80 and 63. These fatigue strength categories lead to damage assessments on the safe side, increasing the fatigue strength of HE220B specimens by one category results in damage index values nearer to unity.

3.3 Connections

3.3.1 Welded joints

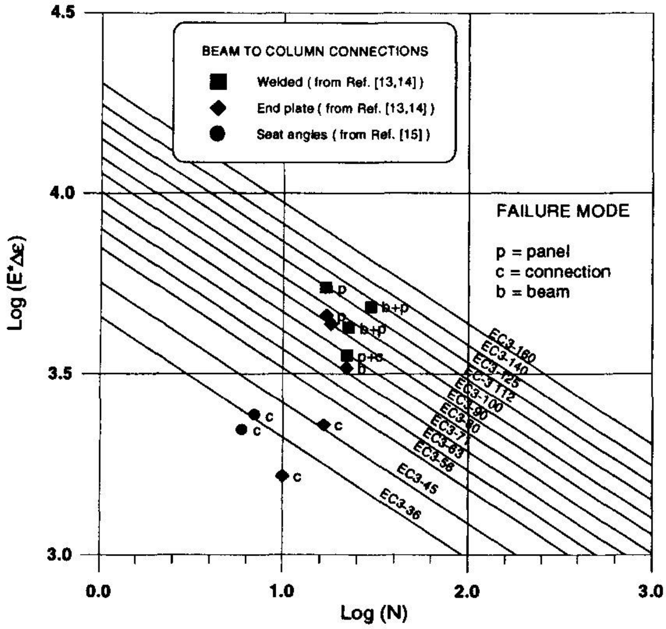
Fig. 3 Fatigue strength of welded joints



An experimental study was carried out at Politecnico di Milano on welded details commonly adopted in structural steelwork. Three types of connections were considerded: fillet welded coverplates (long and short ones) and fillet welds in cruciform joints. Small specimens (400 mm long) were manufactured and tested imposing axial strain cycles with a constant amplitude. Various tests were performed under different strain ranges. Fig. 3 shows some of these test results (together with results for unwelded specimens obtained during the same study), reprocessed according to eq. (3). The base material plots between EC-3 lines 100-125, 100mm ("long") coverplates between EC-3 lines 56-63, 50mm ("short") coverplates between EC-3 lines 45-63, fillet welds in cruciform joints between EC-3 lines 45-56. These results are in good agreement with the classification of the various details by EC-3, where base material is assigned a fatigue strength category ranging between 125 and 160, coverplates to categories ranging between 45 and 63, fillet welds in cruciform joints to category 36 (40-63 by the Italian C.N.R. 10011/86 Code). Of course, the small number of test data did not allow for any regression analysis. This fact, in addition to the absence of residual stresses (due to the small dimension of the specimens), account for eventual small differences between code classification and the results of the present study.

3.3.2 Beam to column connection

Fig.4 Fatigue strength of beam to column connections



It has been tried to apply the same procedure for defining the fatigue strength of beam to column connections[13-15], consisting of welded connections, end plate connections and double seat angle connections. As all these tests were performed under variable amplitude loading according to [6], in order to define the fatigue strength category of each connection re-analysis of test data was carried out adopting Miner's rule, and defining the pertinent EC-3 line a-posteriori, as the one giving, at collapse, a damage index approximately equal to 1.0.

It can be noticed that test data are grouped, depending on the failure mode. The end plate joints from Ref. [13,14] that failed in the connection show a low fatigue strength, similar to that of seat angle connections from Ref. [15]. The other connections (both welded and end plated) show a higher fatigue strength, although the failure mode seems to influence their fatigue behavior. Presently it is tried to enlarge the data base also by collecting and re-analysing test data presented in the literature. Even from these previous results it can however be concluded that the design of connections is critical for a good performance of structures under low cycle fatigue and that, in order to avoid brittle fracture, it should be tried to induce the formation of a plastic hinge in the members, away from the connections. This is of course in good agreement with other results presented in the literature (e.g. [18]).

4. CONCLUSIONS

If an equivalent stress range $\Delta\sigma^* = E\Delta\varepsilon$ is considered, associated with the actual strain range $\Delta\varepsilon$ in an ideal indefinitely elastic behavior of the material, the S-N lines given by Codes for high cycle fatigue can be adopted for interpreting the low cycle fatigue behavior of beams, welded joints and beam to column connections.

Miner's rule can be adopted, together with the previously defined S-N curves and with a cycle counting method (e.g. Rainflow) to define a unified collapse criterion, valid for both high and low cycle fatigue.

The application of these results and of the proposed method for damage assessment to steel structures under seismic loading may lead to an overcoming of seismic design methods based on the behavior factor as shown in [17].

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