A USER-FRIENDLY TOOL FOR FATIGUE ASSESSMENT OF STEEL STRUCTURES ACCORDING TO EUROCODE 3

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ABSTRACT
During the lifetime of a structure, dynamic actions can induce serious fatigue issues for certain structural details. This paper presents the development of a user-friendly tool for fatigue assessment of steel structural details according to Eurocode 3. Stress cycles are evaluated through the rainflow method, by considering the algorithm described in ASTM E1049-85 (2005). Fatigue damage due to these variable stress ranges are calculated based on a linear cumulative fatigue damage rule. The main purpose is to integrate structural stress analysis and fatigue design in a comprehensible manner to current steelwork practice.

Keywords: Fatigue, Eurocode 3, Miner’s rule, rainflow algorithm, equivalent stress range.

INTRODUCTION
During the lifetime of a structure, certain structural details are subject to load cycles which can induce fatigue damage, and consequently affect the structural performance. Thus, in the context of fatigue assessment using Eurocodes, this paper presents a computational tool which allows the computation of fatigue damage in specific details based on the rules prescribed in Eurocode 3 (EN 1993-1-9, 2005), namely through the Damage Accumulation Method.

Fatigue assessment of steel structures in current steel standards are based on the SN curves approach, with typical structural details organized into different categories. Each detail category is represented by the corresponding SN curve, where the fatigue strength $\Delta \sigma$ is a function of the number of cycles, $N$, both represented in logarithmic scale. Then, the fatigue resistance is defined as $N = C \cdot (\Delta \sigma)^m$, where $N$ is the number of cycles of stress range, $\Delta \sigma$, $C$ is the constant representing the influence of the structural detail and $m$ is the slope coefficient of the mean test results line, both constants being related to material and geometry properties of the detail.

In this way, the standard SN curves of Eurocode 3 (EN 1993-1-9, 2005) are classified by the detail category, $\Delta \sigma_C$, value of the fatigue strength at 2 million cycles over constant amplitude, expressed in N/mm², and by the constant amplitude fatigue limit, $\Delta \sigma_D$, at 5 million cycles. The slope coefficient $m$ is equal to 3 for lives shorter than 5 million cycles. The value $m = 5$ is used between 5 million and 100 million of cycles. This value corresponds to the cut-off limit, $\Delta \sigma_L$. Theoretically, all cycles with stress ranges below the cut-off limit $(\Delta \sigma_L)$ do not contribute to the fatigue damage.

In civil engineering applications, real load data (for example, vehicles crossing a bridge) consists of several different stress ranges $\Delta \sigma_i$ (variable amplitude loading history). There are various methods allowing to consider the influence of the different magnitudes on fatigue life.
One of the preferred methods is the rainflow counting algorithm, as standardized in ASTM E1049-85 (2005), due to facility for computer programming. Moreover, current steel standards approaches based on the SN curves include two-slope curves to account for the effect of variable amplitude loading. Thus, if the service loads are well-known, the fatigue verification can be performed on the basis of the damage accumulation by Miner’s rule (Miner, 1945).

PROPOSED METHODOLOGY FOR FATIGUE ANALYSIS

In many civil engineering structures, the existing stress amplitudes on structural details occur owing to the dynamic loads, causing fatigue damage and, for this purpose, a general procedure based on the Damage Accumulation Method (DAM) was implemented in the present software. According to several works (Nussbaumer et al., 2011; Sousa et al., 2013) this method involves the following analysis steps:

- pre-definition of the loading scenario, which has to be done by the user as specified in the design standards or by measurement data;
- identification and classification of structure’s fatigue prone details, according to the SN curves proposed by the Eurocode 3 (2005); moreover, the user should choose between a safe life assessment or a damage tolerant assessment, in order to define the fatigue strength reduction factor, $\gamma_{Mf}$;
- calculation of the stress history in critical structural details, using the theory of elasticity with a simplified structural model or the finite element method for more complex models;
- calculation of stress histograms, representing the number of cycles versus the corresponding distribution of stress ranges, by using a cycle counting algorithm, e.g. the rainflow algorithm (ASTM E1049 - 85, 2005; ESDEP, 1995);
- computation of the fatigue damage, by using a linear damage accumulation model, as proposed by Miner (1945), according to which the damage factor, D, is given by:

$$D = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \ldots = \sum_{i=1}^{k} \frac{n_i}{N_i} = 1.0$$

(1)

where $n_i$ is the number of applied load cycles for a given stress range ($\Delta\sigma_i$) and $N_i$ denotes the number of resisting load cycles for a given stress range. Fatigue failure is reached for $D = 1$.

In order to better assess the damage index value, it is possible to obtain for each block of variable loading an equivalent stress range ($\Delta\sigma_E$), defined as the constant-amplitude stress range that would result in the same fatigue life as for the design spectrum. For SN curves with a unique slope $m$, its computation is straightforward. Thus, by the definition of the Miner’s Rule and the SN curve, $\Delta\sigma_E$ can be computed as follows:

$$\Delta\sigma_E = \left( \frac{\sum n_i \Delta\sigma_i^m}{\sum n_i} \right)^{1/m}$$

(2)
However, as aforementioned, the Eurocodes have bi-linear SN curves to take into account the effect of fatigue damage caused by a greater number of cycles with low stress range. Therefore, considering SN curves with double slope coefficients, the equivalent stress range in this case can be computed as follows (MacDonald, 2011):

$$\Delta \sigma_E = \left( \frac{1}{D} \sum \frac{\Delta \sigma_i^2 n_i + \Delta \sigma_D^2 \sum \Delta \sigma_j^2 n_j}{n_i + \sum n_j} \right)^{1/3}$$

(3)

where $\Delta \sigma_D$ is the fatigue limit for constant amplitude stress ranges at $5 \times 10^6$ cycles.

It is important to highlight that the SN curves from Eurocode 3 (2005) are suitable for the fatigue evaluation of normal stresses or shear stresses, depending on whether the computed amplitudes at the structural detail are normal stresses ($\Delta \sigma$) or shear stresses ($\Delta \tau$).

The main assumption of the above described methodology when using FE analysis is to presume as nominal stresses the stresses obtained in a given direction at some specific point of the numerical model, related to the detail category of the corresponding SN curve.

Figure 1 presents a flowchart of the overall process applied for a typical fatigue assessment on steel highway bridges details, with stress histories obtained from a finite element model.

**RAINFLOW COUNTING METHOD**

Cycle counting is used to summarize variable load-versus-time histories by providing the number of cycles related to various amplitudes that occur. There are several methods for cycle counting, but in the practice, one of the preferred method is the rainflow method, developed by Endo and Matsuishi (1968).

The name of the rainflow method derives from the analogy with the flow of a raindrop along a Pagoda shaped roof (a traditional Japanese building). In this analogy, the water (rain) is allowed to fall from the top onto the roof and the paths followed by the rain are followed. For
each leg of the roof an imaginary flow of water is introduced and its highest point. The flow of water is followed for the outermost starting point first, allowing the water to drop onto any parts of the roof below and continue to drain until it falls off the roof completely. However, if the flow reaches a position where water has drained from a previous flow, it is terminated at that point (ESDEP, 1995).

In order to better illustrate this method, consider the record corresponding to the stress histories ($\sigma – t$) with a vertical $t$-axis, as shown in Figure 2a. In this record, only the local extreme values are represented, where the valleys are associated with odd numbers and the peaks with even numbers.

![Fig. 2 - Rainflow counting method, a) peak-and-valley stress history; b) equivalent stress history in terms of stress cycles (Ribeiro et al., 2012).](image)

Taking this record as reference, the water movement can occur from left to right as well as from right to left, starting always from each peak or valley. The water drop initiates its movement in point 1, tracking the first roof until it reaches a peak or valley; then, the water drop falls vertically till it reaches another roof, and the path of the water is only interrupted when: i) it crosses another raindrop path falling from a higher roof. An example is the path 3-2’, which intersects the raindrop path vertically falling from 2, or ii) it goes through a point where the stress is higher or equal (in absolute value and of the same nature, peak or valley) to the stress at the starting point. As examples from the illustrated stress record, there are the raindrops falling from peak 6 and from valley 3.

Hence, path 5-6 ends after 6, since valley 7 is more negative than valley 5; similarly, the path ends at 3 because peak 4 is more positive than peak 2. A new path cannot be initiated while the previous one has not been completed. Consequently, each full path (1-2-2’-4; 4-5-7; 7-8-8’-10) is counted as half a cycle, with the addition of two half cycles of equal stress range creating a full cycle. The interruptions of the path, such as 2-3-2’, 5-6-5’ and 8-9-8’, compose full cycles. After counting all half and full cycles, it is possible to draw a $\sigma – t$ equivalent record, in terms of stress cycles (Figure 2b). As a result, any stress history can be translated into a stress range spectrum (Nussbaumer, 2011). The rainflow method algorithm is described with details in the standard ASTM E1049-85 (2005).

**EC3 FATIGUE CALCULATOR USER INTERFACE**

The developed tool focused on user-friendly features for the user interface (see Figure 3), which is more efficient and less exhausting to perform various calculations. Data can be imported from external programs, e.g. electronic worksheet. One can control the number of...
decimal places used in the stress history as input for the rainflow algorithm, which affects the final result less than 3%. It is expected that the Stress history units entered by the user should be in Megapascal, due to required unit consistence with the standardized S-N curves.

![Fatigue Damage Accumulation](image1.png)

**Fig. 3 - EC3 Fatigue calculator by the damage accumulation method (DAM).**

Moreover, users may choose the image which best represents the structural detail to be analysed and shown in final report, as illustrated in Figure 4. The details available are from the structural details available on the tables of EN 1993-1-9 (2005).

![Selection of picture](image2.png)

**Fig. 4 - Selection of picture which represents the standard structural detail.**
NUMERICAL EXAMPLES

The process of software testing and validation requires a comparison between the software computed values and those obtained in literature. There are many examples of application of the Damage Accumulation Method in steel structures, both for assessment of existing structures (Kühn et al., 2008; Ribeiro et al., 2006) or the design of new structures (Nussbaumer et al., 2010). Two numerical examples are exemplified in the next sections.

Fatigue assessment of one sided connection with preloaded high strength bolts

Herein, one presents an example from a well-known reference (ESDEP, 1995), in which was considered a sample stress of variable amplitude applied to a detail category 90 with a partial strength factor of $\gamma_M = 1.0$. According to EN 1993-1-9 (2005), this structural detail category may consist, for example, of one sided connection with preloaded high strength bolts ($\Delta\sigma_C = 90 \text{ MPa}$). The stress history used as input is shown in Figure 5.

The results from the cycle counting algorithm are 1 cycle at 120 N/mm$^2$, 1 at 100 N/mm$^2$, 4 at 80 N/mm$^2$, 6 at 60 N/mm$^2$ and 10 at 30 N/mm$^2$, exactly same as the referred work. In order to calculate the total damage accumulation, the sample event was supposed to occur over 1 year. As a result, the number of cycles of each stress range were multiplied by 29,200 (ESDEP, 1995). Then, the application of Miner’s rule leads to a total damage of 0.1169, which differs less than 0.5% from the reference value of 0.1174 (ESDEP, 1995).

![Stress cycle history used as input for program validation (ESDEP, 1995).](image-url)
Fatigue assessment of an old riveted steel bridge

The second example consists of a fatigue assessment of an old riveted steel railway bridge example (see Figure 6) available in a well-known technical report (Kühn et al., 2008). According to the authors, theoretically, after over 100 years of service, there was a motivation for fatigue assessment since the bridge has reached the end of its design working life. Therefore, an assessment of a riveted connection (supposed to be of structural detail category 71) was carried out in the referred technical report to determine the residual service life of the bridge.
The defined spectrum (number of cycles for each stress range) and the fatigue damage computed by the developed software is shown in Tab. 1. In this case was obtained a similar damage value of 0.8766 compared with the one obtained by the authors (0.8678) for a certain period of time (Kühn et al., 2008). Further details can be found in the referenced work.

Table 1 - Computed results of number of cycles for each stress range

<table>
<thead>
<tr>
<th>∆σ (MPa)</th>
<th>Cycles Number</th>
<th>EN 1993-1-9-71</th>
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<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>17</td>
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</tbody>
</table>

Δσ<sub>max</sub> = 93 MPa  Σ 3396000  D = 0.876625455229471

OPEN WORKING GROUP FOR FUTURE IMPROVEMENTS

Researchers and students interested in future improvements related to advanced fatigue assessment approaches in steel structures are invited to collaborate. Free download of the tool is available on GitHub, a Web-based revision control hosting service for software development and code sharing. Users interested in contributing for the software may access the following link: https://github.com/guilhermealenar/ec3FatigueCalc. The software was developed using the Integrated Development Environment (IDE) Microsoft Visual Studio 2015 (Figure 8), which has a free release available (the Community release).
CONCLUSIONS

The main contribution of this computational tool is to offer for engineers a more efficient and practical manner to perform fatigue assessment of steel structures based on SN approach and using the Damage Accumulation Method (DAM). This was accomplished by the development of a user-friendly graphical interface. Also, the availability of standard image library categories allows to classify the structural detail easily.

The developed tool was validated comparing the given results with hand calculations of literature. A good agreement was achieved between those values. Therefore, the purposed software allows the integration of structural stress analysis and fatigue design in a comprehensible manner to current steelwork practice, with a user-friendly graphical interface.

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REFERENCES


