On the fatigue assessment of plain and short fibre/particle reinforced concretes

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ABSTRACT. By reanalysing more than 1500 data taken from the literature, a unifying design curve is proposed to estimate fatigue damage in un-notched plain and short-fibre/particle reinforced concretes subjected to cyclic loading. The considered experimental results were generated by testing both plain and short-fibre/particle reinforced concretes cyclically loaded either in tension, in tension/compression, in compression, or in bending. From a design point of view, the most important feature characterising the proposed standardised methodology is that the mean stress effect is directly accounted for through the maximum stress in the cycle under either tension/compression or bending, and the absolute value of the minimum stress under compression (the above design stresses being normalised through the corresponding static strength). The above strategy resulted in a great simplification of the problem, allowing all the considered experimental results to fall within a narrow scatter band.

SOMMARIO. In questo lavoro sono stati rianalizzati circa 1500 dati sperimentali estratti dalla letteratura con lo scopo di determinatre una nuova curva di progetto adatta a stimare la resistenza a fatica del calcestruzzo (non solo calcestruzzo convenzionale ma anche calcestruzzo rinforzato con particelle/fibre corte) utilizzando come unica informazione sperimentale per la calibrazione della curva stessa la resistenza statica del materiale. I risultati utilizzati per la determinazione di tale curva comprendono prove di fatica in trazione, trazione e compressione, compressione e flessione a tre/quattro punti. Infine, è importante sottolineare come, da un punto di vista progettuale, la curva di fatica proposta nel presente lavoro consenta inoltre di tenere direttamente in considerazione l'effetto di tensioni medie diverse da zero, siano esse di trazione o di compressione.

KEYWORDS. Fatigue; Concrete; Design.

INTRODUCTION

In the civil construction ambit there exist several situations of practical interest in which concretes are subjected to in service time-variable loading (such as, for instance, runways subjected to repeated loads due to passing aircrafts, asphalt concretes subjected to cyclic local pressures resulting from the action of tyres, and the concrete structural parts of bridges cyclically loaded by traveling motor vehicles). Even if the fatigue behaviour of concrete structures was first studied at the very beginning of the last century [1, 2], such a problem has been tackled systematically by the international scientific community solely from the early 50s. Thanks to this large body of work, nowadays, structural engineers engaged in designing concretes against fatigue can take full advantage of the outcomes from several experimental investigations. However, in spite of the large number of experimental data which are available in the

technical literature, examination of the state of the art suggests that the scientific community has not yet agreed a universally accepted strategy suitable for efficiently and accurately designing concretes against fatigue. It is also somehow surprising the fact that, contrary to the scientific community working on the metal fatigue issue, the researchers investigating the fatigue behaviour of concretes have not yet defined a unified symbolism to be adopted to describe and quantify the damaging effect on concrete structures of cyclic loadings.
In this complex scenario, the present paper attempts to propose a novel design fatigue curve suitable for estimating fatigue strength of concretes where the only experimental information required to accurately perform the fatigue assessment is the static strength (under either tension, compression, or bending).

INVESTIGATED EXPERIMENTAL RESULTS

By performing a systematic bibliographical investigation, more than 1500 experimental results were selected from the technical literature and stored in a ad-hoc build database. The re-analysed experimental results were generated by testing plain concretes as well as short fibre/particle reinforced concretes subjected to either cyclic tension (T), cyclic tension/compression (T/C), cyclic compression (C), or cyclic three (3PB)/four (4PB) point bending. The reader is referred to Refs [3-34] for a detailed description of the post-processed experimental results.

MEAN STRESS EFFECT IN THE HIGH-CYCLE FATIGUE REGIME

To investigate the influence of superimposed static stresses on the fatigue behaviour of concretes, the selected experimental results were initially re-analysed, for a probability of survival, P_S, equal to 50%, in terms of endurance limit amplitude, $\sigma_{A,50\%}$, extrapolated at $N_{Ref}=2\cdot10^6$ cycles to failure, this value for the reference number of cycles to failure being the one suggested by Eurocode 3 [46] to be used to perform the fatigue assessment of steel structural details. The statistical reanalysis was performed, for any data sets, under the hypothesis of a log-normal distribution of the number of cycles to failure for each stress level with a confidence level equal to 95% [35, 36].
The endurance limit amplitudes experimentally determined, for P_S=50%, under $\sigma_{max}>0$ are summarised in the chart of Fig. 1a. This diagram plots the $\sigma_{A,50\%}$ to σ_S ratio against $R=\sigma_{min}/\sigma_{max}$, static strength σ_S being taken either equal to the material tensile static strength, f_T, under cyclic axial loading or equal to material bending static strength, f_B, under cyclic bending. As to the strategy followed to normalise the above diagram, examination of the state of the art clearly indicates that, given a concrete, its fatigue strength is somehow proportional to its static properties. It is well-known that the static strength of a concrete under compression is about an order of magnitude larger than the corresponding static strength under either tension or bending. Accordingly, the hypothesis was formed that the tensile part of the cycle is the most damaging one also in those load histories characterised by $\sigma_{max}>0$ and $\sigma_{min}<0$, this holding true independently from the load ratio, R, associated with the loading cycle being assessed. The diagram of Fig. 1a clearly proves the validity of the above assumption, the adopted normalisation strategy allowing the experimental data to align themselves along a straight line. The linear trend shown in Fig. 1a suggests that, given the amplitude of the applied loading cycles, the associated fatigue damage extent increases as the magnitude of the mean stress increases (i.e., as R increases).
By following a strategy similar to the one adopted to build Fig. 1a, the chart of Fig. 2b shows the effect of non-zero mean stresses under compressive cyclic loadings (i.e., under $\sigma_{max}\le0$). Such a chart makes it evident that, when measured in terms of amplitudes, the fatigue strength of concretes loaded in cyclic compression decreases as the mean stress decreases. Under such circumstances as well, the experimental endurance limits generated by testing both plain concretes and concretes containing particles can be summarised through a linear relationship between $\sigma_{A,50\%}/f_C$ and load ratio R, f_C being the material static strength under compression.
In order to tackle the mean stress effect problem from a different angle, the selected experimental results were also re-analysed, for P_S=50%, in terms of $\sigma_{MAX,50\%}$ (under $\sigma_{max}>0$) and $|\sigma_{MIN,50\%}|$ (under $\sigma_{max}\le0$), these two stress quantities being the endurance limit at $N_{Ref}=2\cdot10^6$ cycles to failure determined in terms of σ_{max} and $|\sigma_{min}|$, respectively. The normalised endurance limit vs. load ratio diagrams reported in Fig. 1c and 1d make it evident that the use of $\sigma_{MAX,50\%}$ (under $\sigma_{max}>0$) and $|\sigma_{MIN,50\%}|$ (under $\sigma_{max}\le0$) allows the experimental data to fall within an error band of ±20%, the average value of the normalised endurance limit being equal to 0.63 under $\sigma_{max}>0$ and to 0.6 under $\sigma_{max}\le0$. As to the above data scattering, it has to be said that, when the fatigue design of different engineering materials than concretes is performed in terms of stresses, the most accurate fatigue criteria are seen to be capable of high-cycle fatigue estimates falling within an error

interval of ±20% [37]. If this error level is assumed to be acceptable also for concretes, the diagrams of Fig. 1c and 1d then suggest that the mean stress effect in concrete fatigue can efficiently be taken into account by addressing the problem in terms of σ_{max} under $\sigma_{max}>0$ and in terms of $|\sigma_{min}|$ under $\sigma_{max}\leq 0$.

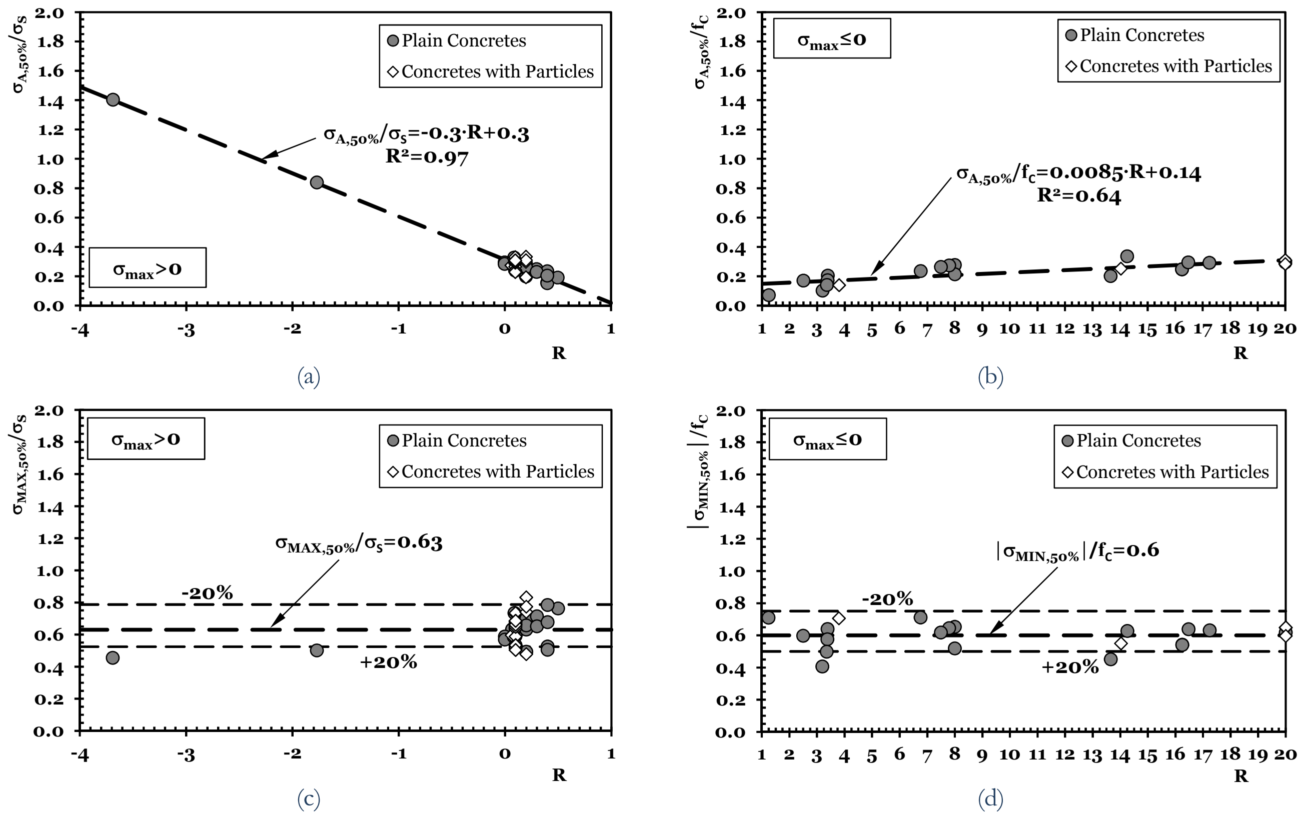

Figure 1: Endurance limit vs. load ratio diagrams plotted, for a probability of survival equal to 50%, in terms of both amplitude, $\sigma_{A,50\%}$ (a, b), maximum stress, $\sigma_{MAX,50\%}$, under $\sigma_{max}>0$ (c), and minimum stress absolute value, $|\sigma_{MIN,50\%}|$, under $\sigma_{max}\leq 0$ (d).

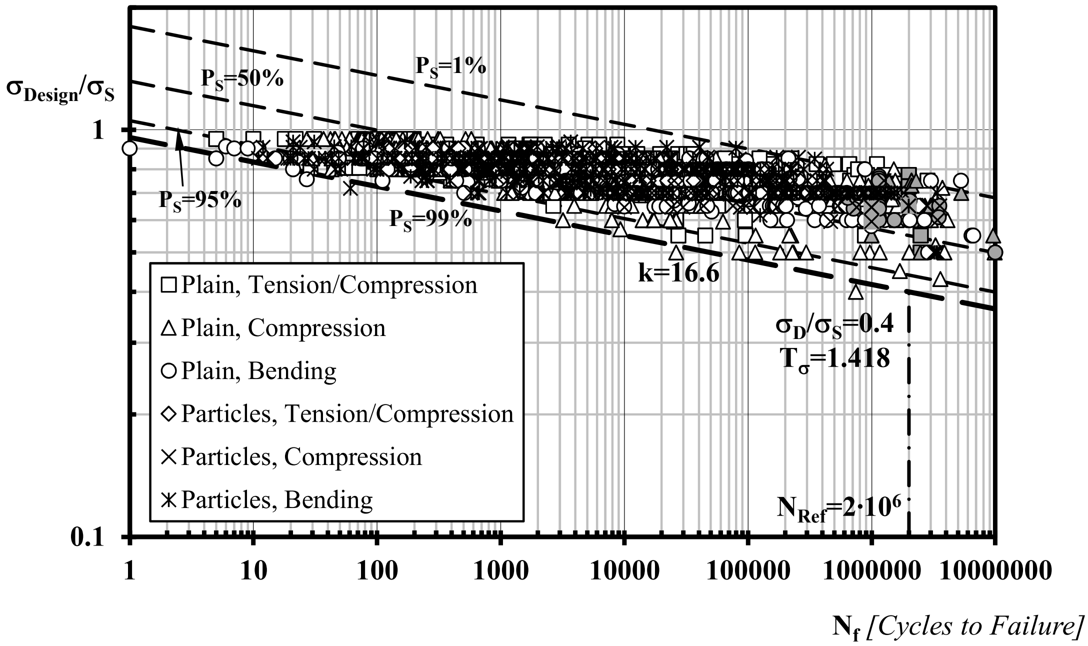

Figure 2: Unifying Wöhler diagram to perform the fatigue assessment of unnotched concretes (grey markers=run outs).

To conclude, it can be said that the reasoning summarised in the present section, which is fully based on the experimental evidence, strongly supports the idea that the fatigue assessment of concretes (with and without particles) can be efficiently performed by determining the design stress, σ_{Design}, according to the following definitions:

under $\sigma_{max}>0 \Rightarrow \sigma_{Design}=\sigma_{max}$ (1)

under $\sigma_{max}\leq 0 \Rightarrow \sigma_{Design}=|\sigma_{min}|$ (2)

Finally, the fact that the average value of the $\sigma_{MAX,50\%}$ to σ_S ratio (under $\sigma_{max}>0$, Fig. 1c) and the average value of the $|\sigma_{MIN,50\%}|$ to f_C ratio (under $\sigma_{max}\leq 0$, Fig. 1d) are very close to each other indicates that, in relative terms, the fatigue assessment of concretes can accurately be performed without the need for distinguishing between compressive and tensile loading cycles, provided that the above endurance limits are coherently normalised.

UNIFYING DESIGN CURVE

In the previous section, by addressing the concrete fatigue problem solely in terms of endurance limits extrapolated at $N_{Ref}=2\cdot 10^6$ cycles to failure, we came to the conclusion that, from a design point of view, fatigue damage can efficiently be estimated by calculating the design stress, σ_{Design}, according to definitions (1) and (2). Further, the fact that, as shown in Fig. 1c and 1d, the average value of the normalised endurance limits is equal to about 0.6 (this holding true both under $\sigma_{max}>0$ and under $\sigma_{max}\leq 0$) strongly supports the idea that fatigue lifetime of concretes with and without particles can accurately be estimated by considering a unique reference curve. In order to check the validity of the above idea, the Wöhler diagram of Fig. 2 summarises about 1500 experimental results, where the adopted normalisation process is the same as the one already discussed in the previous section. Fig. 2 makes it evident that the use of the design stress calculated according to definitions (1) and (2) allows the considered fatigue results to fall within a narrow scatter band, this holding true independently from material and type of applied loading. In particular, as shown in Fig. 2, the fatigue data distribution is seen to be characterised by a T_σ value equal to 1.418, T_σ being the scatter ratio of the endurance limit for 90% and 10% probabilities of survival. As to this level of scattering, it is worth mentioning here that the available standard codes [38] and recommendations [39] specifically devoted to the fatigue assessment of steel welded joints are compiled by assuming a reference value for T_σ equal to 1.5 [40].
To conclude, it can be said that the low level of scattering characterising all the experimental results summarised in the Wöhler diagram of Fig. 2 strongly supports the idea that the proposed reference curve, which is based on design stress σ_{Design} calculated according to definitions (1) and (2), can be considered as a powerful engineering tool suitable for safely and accurately designing un-notched plain and short fibre/particle reinforced concretes against uniaxial fatigue.

CONCLUSIONS

- ✓ Under $\sigma_{max}>0$, the maximum stress in the cycle, σ_{max}, is a stress quantity which can confidently be used to perform the fatigue assessment of plain and short-fibre/particle reinforced concretes.
- ✓ Under $\sigma_{max}\leq 0$, the absolute value of the minimum stress in the cycle, $|\sigma_{min}|$, allows plain and short-fibre/particle reinforced concretes subjected to cyclic compression to accurately be designed against fatigue.
- ✓ Both σ_{max} and $|\sigma_{min}|$ are seen to be capable of accurately modelling the mean stress effect in concrete fatigue.
- ✓ The relatively low level of scattering characterising the unifying fatigue curve proposed in the present paper (see Fig. 2) and determined by post-processing about 1500 experimental results suggests that such a design curve can confidently be used in situations of practical interest to design un-notched concrete structures subjected to in-service cyclic loadings.

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