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Shear fatigue behaviour of reinforced concrete elements without shear reinforcement

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ABSTRACT

The shear fatigue behaviour of reinforced concrete elements without stirrups is dealt with in this paper. Existing experimental results have shown significant differences between the static and fatigue failure mode of reinforced concrete. It has been reported that beams without shear reinforcement designed to have a ductile failure in flexure are able to develop a brittle shear failure when they are subjected to repeated loads. Shear fatigue of reinforced concrete beams without stirrups is a complex process from the mechanical viewpoint that has not been fully understood yet. Typical shear fatigue failure takes place by inclination of a flexural crack in the shear span and its progressive propagation into the compression zone until its destruction when its depth is too small to resist the applied compression force. This process is analyzed in this paper by means of a mechanical model that helps in understanding the formation of a diagonal crack and its propagation with load cycles. The failure mode and residual strength after diagonal cracking are studied as a function of the stress state at the tip of the effective diagonal crack.

1. Introduction

Bridge decks, approach slabs, wind towers, or offshore structures are reinforced concrete elements subjected to a high number of load cycles. Therefore, their performance can be affected by fatigue effects. Nevertheless, even the most advances structural concrete codes do not typically include a verification of the shear fatigue safety, or those which do (Model Code and Eurocode) still prefer purely empirical formulations instead of advanced mechanical models [1]. *S*–*N* curves or Goodman diagrams are the preferred scheme followed by the codes to verify fatigue limit state. These concepts allow for evaluating the resisted number of cycles as a function of the minimum and maximum applied loads. Although such formulations are simple since the practical viewpoint, they do not actually provide a physical understanding of the complex shear fatigue behaviour.

Shear fatigue behaviour of reinforced concrete elements without shear reinforcement is a rather complex process which involves a large number of variables. This process was first described by Chang and Kesler [2,3] from their extensive experimental campaign on beams subjected to four-point bending fatigue. The first stage of the process consists of the formation of a diagonal crack from the inclination of an existing flexural crack at the shear span. This shear crack then propagates, on the one hand, to the compression zone and, on the other hand, to the support running approximately parallel to the longitudinal reinforcement. Fatigue failure occurs when the propagation of the diagonal crack has reduced the depth of the compression zone so that it cannot resist the compressive stresses acting on it. This failure mode was called *shear-compression* fatigue by Chang and Kesler. Furthermore, some tests also showed that the diagonal crack was able to develop fully instantaneously. This second failure mode was called *diagonal-cracking* fatigue failure by Chang and Kesler. Fatigue fracture of the longitudinal reinforcement can also take place, which is a function of the stress amplitude [4,5]. In addition, recent researches have experimentally shown the likelihood and failure mode of prestressed concrete beams under cyclic shear [6,7].

In this paper, a mechanical approach is proposed to investigate the shear fatigue process of reinforced concrete beams. Because of the complexity of the process, the model does not only focus on the estimation of the shear fatigue strength, but also is intended to help in the understanding of the phenomena involved in the formation and propagation of the diagonal crack. Although many researchers consider that shear fatigue failure is reached with the formation of the diagonal crack, the authors believe that it is necessary to distinguish between the instant of diagonal cracking and the final shear failure in order to fully understand the shear fatigue

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process. The difference between these two instants can be significant in some cases and, furthermore, it can be very useful for practical situations where decisions regarding the repair or replacing of a structural element are to be made.

In order to assess the number of cycles to diagonal cracking, a model is formulated as a function of the stress state at the tip of the flexural crack supposed to be the one that leads to the diagonal crack. The result of this model is presented in the form of a simplified but mechanically based *S–N* equation. The second part of the approach presented in this paper analyzes the propagation of the diagonal crack from the instant of diagonal cracking to final failure. This analysis is based on concrete fracture mechanics concepts. The model makes it possible to assess the stability of the diagonal crack depending on the stress intensity factor (SIF) at the tip of the effective diagonal crack. The model capabilities are analyzed by means of comparisons with a comprehensive database collected by the authors, including the existing fatigue tests carried out on reinforced concrete beams without shear reinforcement [2–16].

2. Experimental evidence

In order to understand the shear fatigue process, the experimental result obtained in test VA1 carried out by the authors at UPM [15] is briefly described. The test consisted of a simple supported reinforced concrete beam without shear reinforcement subjected to four-point bending fatigue. The concrete compressive strength was 25 MPa and the maximum aggregate size was 20 mm. The cross section was 0.30 m deep ($d = 0.25$ m) and 0.30 m wide, with a span length of 5 m. The steel reinforcement ratio was $\rho = A_s/bd = 0.025$ and the shear span-to-depth ratio was $a/d = 5.40$, where a is the distance between the point load and support axes. The maximum and minimum applied loads were 60 kN and 25 kN, respectively. The load was applied with a hydraulic actuator and a steel plate of $0.15 \times 0.30 \times 0.05$ m was placed between the actuator and the specimen. The test was initially aimed at obtaining fatigue failure of concrete in compression but shear-compression failure occurred prematurely. The evolution of the specimen during the test is represented in Fig. 1a. Vertical flexural cracks formed in the first cycles along the span length, including the shear spans. A diagonal crack formed suddenly at one shear span after 77,000 load cycles. This crack initiated from the tip of an existing flexural crack at a section 315 mm from the load application point axis. The formation of the diagonal crack did not lead to failure and the test could be continued as the diagonal crack propagated into the compression zone and to the support. Final fatigue failure took place after 170,718 cycles by destruction of the compression zone when its depth had been reduced to approximately 100 mm. A view of the failure instant is given in Fig. 1b. The result obtained in test VA1 shows the typical stages of the shear fatigue process with shear-compression failure, with significant residual fatigue strength after diagonal cracking.

Tests carried out by Chang and Kesler [2,3] included 64 beams (0.102 m wide, 0.152 m deep, $d = 0.137$ m, $a/d = 3.72$) with three values of the steel reinforcement ratio ($\rho = 0.0102$, 0.0186 and 0.0289). The experimental number of cycles to diagonal cracking is represented in Fig. 2a as a function of the normalized maximum shear force ($V_{max}/bdf_c^{0.5}$). The residual number of cycles after diagonal cracking is also represented in Fig. 2b, where it can be observed that many specimens failed as soon as the diagonal crack appeared (diagonal-cracking failure) but others presented a significant residual strength after diagonal cracking. The observation of Fig. 2 does not allow the derivation of clear conclusions regarding the failure mode as a function of shear force levels. Moreover, the scatter increases significantly when experimental results obtained by other researchers are included in the analysis, as shown in Section 3.

3. Shear fatigue strength according to standards

The typically reported fatigue failure of reinforced concrete beams has been due to the brittle fracture of the longitudinal reinforcement. Accordingly, the fatigue verification of the steel reinforcement has been included in codes of practice for several decades. The verification of fatigue ultimate limit state in current codes [17–19] is mostly based on empirical *S–N* formulations (they provide the maximum bearable number of cycles as a function of the stress range), which have demonstrated good performance for metals. Nevertheless, experimental works have shown that shear fatigue failure can also take place in beams without shear reinforcement well before that instant. A comprehensive literature review has been carried out by the authors and existing tests with fatigue shear failure have been collected and summarized in Table 1. The stress range at the longitudinal reinforcement of the considered specimens has been calculated and represented over the number of cycles to failure in Fig. 3, where it can be observed that shear failure took place before the expected fatigue fracture of the reinforcement (according to the *S–N* curve of reinforcing steel suggested by the Eurocode-2). Furthermore, an additional analysis of the ductility check of considered tests (x/d at failure, listed in Table 1) shows that the mode of fatigue failure does not depend on the static failure mode, namely, elements designed to develop a ductile flexural static failure can present shear failures under cyclic loads. In spite of the different nature of fatigue process in metals and concrete, codes of practice have introduced shear fatigue verification in the form of *S–N* curves, i.e. the number of cycles to shear fatigue failure is a function of applied shear forces. Such a statement also applies for the Model Code of the International Federation for Structural Concrete, which includes the most recent

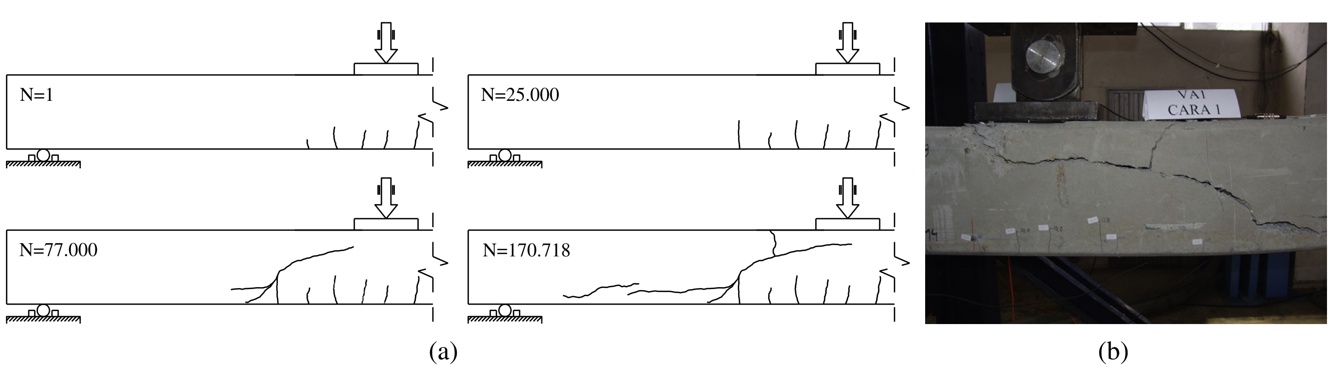

Fig. 1. Analysis of test VA1 from [15]: (a) evolution of crack pattern; (b) view of the shear crack after shear-compression fatigue failure.