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Stress distribution and resistance of lap splices under fatigue loading

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ABSTRACT

Straight lap splices are employed in reinforced concrete to transfer loads from one steel reinforcing bar to another by bond between the embedding concrete and the two bars along a lapped length. In the last years, some concerns have arisen on the possibility of fatigue of bond-related structural problems, in part due to the very few models available to evaluate the bond fatigue strength. Regarding design standards, some codes for off-shore structures have addressed such a specific topic, by means of a simple S-N formulation. Besides that, recent experimental research has shown that fatigue failures of lap splices can occur because of the poor confinement conditions which result in a small static bond strength leading to high relative stress levels sensitive to fatigue. In the present paper, a mechanical model is proposed to understand the fatigue behaviour of lap splices. The model solves the lap splice problem by taking into account the particular equilibrium, compatibility, constitutive and boundary equations, which produce a different solution than other bond-related problems (anchorages, tension stiffening) in terms of stress distribution along the lapped length. For the local bond-slip behaviour, a cycle-dependent formulation is used for the increase of slip with load cycles and the fatigue failure criterion. The model is able to reproduce the real bond stress distribution, which is nonuniform along the lapped length, and the process of redistribution that takes place with load cycles. It is shown that the redistribution process is responsible for higher fatigue strength than that calculated under the assumption of uniform stress distribution.

1. Introduction

Fatigue of reinforced concrete may be due to either fatigue of concrete or fracture of the steel reinforcement [1]. Even though most practical experience and research have shown that fatigue of the steel bars is usually the governing failure mode [2,3], increasing concerns regarding possibility of concrete fatigue failures have fostered research on such a topic. Fatigue of steel reinforcement (like other metals and linear materials) can be well predicted by S-N curves, which provide the number of load cycles to failure as a function of the stress oscillation [4]. In case of cycles with different stress range during the service life, the Miner's rule of linear damage accumulation [5] can be applied. Concrete fatigue (compression, shear, bond, etc.) differs significantly from that of the steel due to the nonlinear behaviour of concrete. Before specifically addressing fatigue of bond between concrete and reinforcement for lap splices (which is the focus of this paper), the main aspects of concrete fatigue are firstly introduced for concrete in compression, since it is probably the best known case of the fatigue process of concrete and its structural implications.

In compression, fatigue of concrete has been described as a progressive microcracking mechanism which results at the macroscopic level in the formation of residual strains and stiffness reduction with the number of load cycles until final fatigue failure [6]. Experimental results have shown that the severity of the microcracking deterioration of concrete depends strongly on the stress level, rather than on the stress oscillation as typical of metals [7,8]. Because of the complexity of the fatigue mechanics of concrete, S-N-based approaches have been proposed to estimate the fatigue strength as a function of the stress limits of the cyclic load [9,10]. Despite such S-N formulations provide an accurate estimate of fatigue strength under constant stress limits, the nonlinearity and stress-dependence of concrete fatigue makes it inappropriate to adopt a linear damage accumulation rule for variable stress limits. It has been shown that the Miner's rule leads to either unsafe or conservative results depending on the stress history [11]. Instead, energy- [12] or strain-based [13] damage accumulation approaches have provided good results, but their direct application to practical cases is not straightforward and most design codes are still based on S-N curves without an explicit consideration of the influence of the nonlinear damage accumulation. The former can result in unrealistic, generally overconservative estimation of the fatigue strength of concrete because fatigue produces a progressive redistribution of stresses whose beneficial influence is not considered [14].

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Nomenclature

A_c	concrete area
A_s	steel area
E_c	concrete modulus of elasticity
E_s	steel modulus of elasticity
N	number of load cycles
F	load
d	effective depth
l_b	anchorage length
l_s	lapped length
n	modular ratio
s	relative slip
s_1	slip corresponding to τ_u
x	abscissa
Φ	diameter of steel reinforcement
ε	strain
ρ	steel reinforcement ratio
σ	stress
τ	bond stress
τ_f	negative frictional bond stress
τ_u	static bond strength

Subscripts

$_0$	initial
$_c$	concrete
$_{max}$	maximum load
$_{min}$	minimum load
$_s$	steel

An overview of the fatigue effect on a reinforced concrete section in bending can be explained with the help of Fig. 1, as described by Zanuy et al. [13]. The positive influence of the capacity for redistribution of stresses is responsible for higher fatigue strength than that estimated by introducing the stress levels of the most initially stressed layer into an S-N curve. The nonlinear stress-dependent deterioration of concrete at different fibers results in a redistribution of stresses from the initially most stressed layers at the top of the section to less damaged layers within the compression zone. Therefore, each concrete layer is actually subjected to cycles of variable stress limits during the fatigue life. Since the most initially stressed top part of the section progressively carries smaller stresses, its fatigue life is longer than the one corresponding to the initial stress levels. So far, the former beneficial effect has been recognized by the Model Code [15] since its 1990 version [9]. The Model Code includes a stress gradient factor which allows reducing the stress level of the most loaded fiber before it can be introduced into the S-N curve. Despite the availability of a simplified approach like the stress gradient factor, most design codes for structural concrete have not even adopted any similar approach so far [10,16]. The undesired consequence is that fatigue of concrete might be an issue governing design in some unjustified cases if the design criterion does not account for the real fatigue process of concrete [17].

The above description makes it clear how research can help in understanding the real fatigue sensitivity of concrete and preventing unjustified alarms in normal design cases. For the last years, a similar research need has arisen on fatigue of bond between concrete and ribbed reinforcing bars. First experimental studies from cyclic pull-out tests [18–20] demonstrated that fatigue failure of bond can occur as a result of a damaging process with many similarities with fatigue of concrete in compression: (a) progressive damage of the steel-concrete interface is observable at the macroscopic level by an increase of relative slip with number of load cycles, (b) fatigue of bond depends on the stress level rather than on the stress oscillation.

Bond between concrete and steel reinforcement governs different structural problems: tension chord of a reinforced concrete member in bending, anchorage of steel bars embedded in concrete, lap splices, etc. In such situations, the bond stress distribution along the bonded length might be different from that of a pull-out test, which also recalls the different fatigue response between a reinforced concrete section in bending and a concrete cylinder under constant stress-limit cyclic load. In fact, fatigue loading also produces a redistribution of bond stresses which makes insufficient the employ of S-N curves to evaluate fatigue bond strength. Zanuy et al. [21] have analyzed the recent experimental results from fatigue tests on anchored bars [22,23] and they have confirmed that the nonuniform bond stress distribution along the bonded length plays a decisive role in the fatigue strength of the anchorage. Because the bond stress distribution is not uniform and the fatigue deterioration (cyclic slip increase) depends on the stress level, a redistribution process develops [24] and final fatigue strength is different than that obtained by assuming uniform bond stresses.

There is lack of specific design rules to evaluate fatigue of bond. Only few standards like the Norwegian code for off-shore structures [25] have addressed bond fatigue with S-N-based formulations. The problems of the tension chord and the anchorage under repeated loading have been addressed by the authors' research group in previous works [21,26]. In the present paper, the effect of fatigue on lap splices is dealt with, which is possibly the bond-related problem on which more concerns on fatigue have been discussed in the last years [27]. Though real fatigue problems have not been reported, many fatigue failures in laboratory tests have been assigned to bond [28] and there are structural details of off-shore structures, railway bridges or elements supporting rotating machines where significant number of load repetitions are possible.

Because the severity of bond fatigue depends on the relative stress level, the quasi-static bond strength plays a big role (the smaller the bond strength, the higher the relative bond stress level). In turn, the bond strength is influenced by the confinement conditions, which can be provided by the concrete cover, the presence of stirrups, external strengthening or external pressure. Lap splices are the bond-related situation where the confinement conditions are among the poorest, since the concrete cover is limited and external pressure (provided by e.g. the support reactions in anchorage zones) cannot be present. Recent experimental results have shown that fatigue strength of lap splices can be an issue and strengthening methods have been investigated to increase the fatigue strength by improving the confinement [29].

The fatigue strength of lap splices is studied in this paper by a model which is able to reproduce the nonlinear bond stress distribution over the bonded length and the progressive slip increase with number of load cycles. The model allows determining the resistant number of cycles in a realistic way as it is shown from comparison with experimental results.

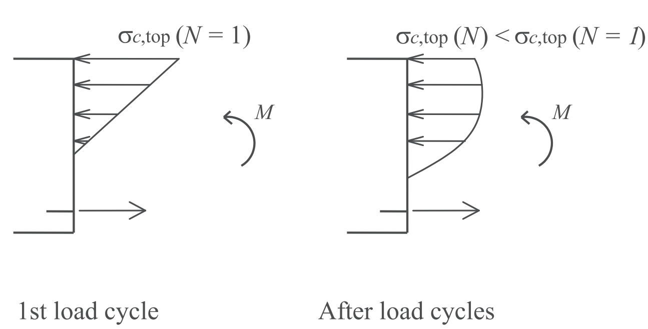

Fig. 1. Effect of fatigue loading in a reinforced concrete section in bending.