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Engineering structures high-cycle fatigue life prediction of reinforced concrete deep beams

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ABSTRACT

Concrete elements deteriorate as a result of continuous application of compressive fatigue loads. Irreversible deformation accumulates; hence, the effect on embedded steel reinforcing bars capacity and concrete resistance should be accounted for in the fatigue analysis of concrete structures. Experimental investigations were conducted to study the fatigue behaviour of eight small-scale reinforced concrete deep beams with a shear span to effective depth ratio of 1.25. Percentages of the diagonal cracking load from monotonic tests were used as fatigue loads. The deformation evolution within the shear spans of the deep beams were obtained by estimating the average principal and shear strain evolutions from the strain transformation analysis of LVDT (Linear Variable Displacement Transformer) data. Midspan deflections and reinforcement strain evolutions with proximity to a major concrete crack location were obtained. In all beams, failure occurred with fracture of the longitudinal reinforcement at the intersection with the major concrete crack. Maximum strain evolutions for shear reinforcement measured at regions around the bends were observed to be lower than the strain evolutions observed in the longitudinal reinforcement. This was attributed to the governing arch mechanism common with deep beams.

The strut and tie method was modified to predict the fatigue life of the deep beams tested by modifying the constitutive models and effectiveness factor of concrete with fatigue damage models. To achieve this, the irreversible compressive fatigue strain in concrete is considered as a pseudo-load. The crack initiation life and the progressive crack growth of steel reinforcement are accounted for using strain-life models and linear elastic fracture mechanics, respectively. Within the developed algorithm, failure will occur when one of the evolving forces in either the concrete strut or steel reinforcement approaches the corresponding residual resistance capacity.

1. Introduction

Investigations of the behaviour of reinforced concrete elements subjected to fatigue loading began in the twentieth century. Due to complex observations in the performances of the constituent materials, further interests in this field of study have evolved. From previous studies [1–3], failure of reinforced concrete elements due to the fracture of reinforcement at their intersection with concrete cracks, crushing of concrete, and excessive evolutions of diagonal tension cracks have been reported as modes of fatigue failure.

1.1. Mechanism of fatigue failure

The failure mechanisms observed in previous tests conducted on reinforced concrete beams were reported to be significantly influenced by the shear span to effective depth ratio (a/d), the stress ratio (ratio of the minimum stress to maximum stress), the reinforcement ratio, and the magnitude of fatigue load [4–6]. Fracture of the tensile reinforcement was observed to occur within the region of maximum moment within beams when subjected to smaller fatigue loads. On the other hand, shear failure due to diagonal cracking occurred under high fatigue loads [7]. The use of different reinforcement ratios have also been reported to influence the failure mechanisms [8]. For example, while lower reinforcement ratios are governed by the fracture of the reinforcement, heavily reinforced concrete members may fail due to crushing of concrete or diagonal tension cracks.

Reports on fatigue tests conducted on beams with shear reinforcement and having shear span to effective depth ratios greater than 2.0 showed increases in the shear reinforcement strains as diagonal or inclined cracks emanated [1–3]. The fatigue load transfer was described to involve a truss mechanism in which shear forces were transmitted by the shear reinforcement from one

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surface of an inclined compressive strut to an adjacent strut. Depending on the average induced strains or stresses in the reinforcement intersecting the diagonal cracks, localised crack growth in the shear reinforcement and widening of concrete cracks occurred. Fracture of the shear reinforcement typically occurred thereafter. However, beams with shear span to effective depth ratios lower than 2.0 were governed by arch mechanism and did not exhibit shear reinforcement fracture at failure [9].

Okamura et al. [1], Okamura and Ueda [2], and Ueda [3] reported that the increase in the shear reinforcement strain was proportional to the logarithm of the number of cycles leading to fracture, especially at bends. As the shear reinforcement fractured, collapse of the beams occurred where the remaining stirrup legs intersecting the widened inclined cracks were insufficient to withstand the applied maximum fatigue load. As such, the fatigue behaviour of shear reinforcement in terms of its maximum strain evolution up to yield was considered as a fatigue limit state. Models developed and reported by Okamura et al. [1], Hawkins [4], Higai [9], and Ruhnau [10] for estimating the strain within a shear span at any given cycle up to failure are used in the literature and codes of practice for this purpose.

Fatigue failure of deep beams with shear span to effective depth ratios of 1.0 and 1.5 were observed to fail under fatigue loading by crushing of concrete compressive struts, diagonal tension, or fracture of longitudinal reinforcement. No fracture of shear reinforcement was observed in any of the specimens [5,6]. In the tests conducted by Teng et al. [6], high-strength deformed steel bars and plain round steel bars were used as shear reinforcement in each shear span per beam. Results and crack patterns on both shear spans revealed no substantial difference. It was also observed that the shear reinforcement in the deep beams did not yield at failure.

An illustration of the behaviour of shear reinforcement in deep beams under fatigue loading can be observed from Higai's report [9] on moving load tests. According to Higai [9], as the distance between the moving load and the support reduced, the observed shear strength increased remarkably. Local compressive concrete stresses were also observed to develop in the vertical direction within the shear span; hence, decreasing the principal tensile stress in the concrete. In addition, it was reported that strains in stirrups decreased as the distance between the support region and loading point reduced. These observations are analogous to clamping or transverse compression stresses in deep beams under static loads [11,12]. However, further investigation is still required in order to understand the fatigue deformation of deep beams.

1.2. Design for fatigue resistance

Deep beam can be designed appropriately and conservatively under static loads using the strut and tie model. Basically, the required concrete section sizes and amount of reinforcement (dimensions of load transfer path) are obtained from the stresses estimated from the static loading conditions at failure (Ultimate Limit State) [13]. Under fatigue loading, the stresses induced in the load transfer paths are estimated from the proposed or given fatigue load (usually lower than the expected monotonic load at failure). The stresses in these paths are further normalised with the material strengths in order to obtain stress levels needed in fatigue models. As a means of fatigue damage resistance verification, the normalized stresses from fatigue loads are implemented into their corresponding fatigue stress-life models in order to obtain the number of cycles that will result in local deformation by crushing (in case of concrete) or fracture (in case of steel). For an appropriate design, the number of cycles leading to failure obtained is ensured to be more than the number of cycles expected for service life. To achieve this, the volumes of materials (section size and amount of reinforcement) are generally increased, if need be [13].

The use of S-N models do not account for damage evolution of the structural element [14,15]. The norm in fatigue design of structures using stress-life models neglects the influence of irreversible strain accumulation in concrete which may be significant in fatigue life prediction. Further, knowledge of the deformation evolution within the shear spans of deep beams in terms of shear strains, principal tensile strains, and principal compressive strains under fatigue loading are expedient in understanding the behaviour of deep beams under fatigue loading, since their resistance capacities may be governed by the behaviour within the shear spans.

In this paper, the influence of load level, stress ratio, and longitudinal reinforcement ratio on the fatigue behaviour of deep beams with shear-span to effective depth ratio of 1.25 are investigated experimentally. An approach is developed using strut and tie analysis for predicting the fatigue life of deep beams. The evolution of irreversible strain accumulation, concrete strength and stiffness degradation, and reinforcement crack growth are accounted for in this approach.

2. Experimental program

2.1. Test specimens

In this investigation, beams with dimensions of $175 \times 250 \times 700$ mm and an a/d value of 1.25 were used for fatigue tests (Fig. 1). The properties of the beams tested are given in Table 1 (columns 1–7). The reinforcement provisions used for the beams surpassed the minimum required in CSA A23.3-04 11.2.8.1 and 11.2.8.2 for shear, 10.5.1.2 for flexure [16], EC-1-1 (2004) 9.2.2 and 9.2.1.1 [17] for shear and flexure respectively, and ACI [18] Section R9.6.3.1 and R9.6.1.2 for shear and flexure respectively.

Adequate anchorage was provided based on code requirements in CSA- N12.13.1, N12.13.2 (shear reinforcement anchorage) [16], N12.5.2 (flexural reinforcement anchorage). The anchorage provisions also satisfied EC2-1-1 (2004) clause 8.5(1) and (2) for shear reinforcement and EC2-1-1 clause 8.4.1 (1) P for longitudinal reinforcement [17]. ACI Table 25-3-1 and Table 25.3.2 [18] for longitudinal and shear reinforcement, respectively were also used as provision benchmarks. Longitudinal reinforcement ratios of 0.45%, 0.90%, and 1.40% were provided, while 0.2% was used as the shear reinforcement ratio.

From Table 1, the first three beams (CONT-1 to -3) having longitudinal reinforcement ratios of 0.45%, 0.90%, and 1.40%, respectively, were tested monotonically, in order to obtain the load, corresponding to the diagonal cracking load. Once the cracking load was attained (based on readings from the LVDTs in tension), results from further increases in loading were not required. Percentages of the maximum diagonal cracking load were then used to define the fatigue loads for other beams with similar longitudinal reinforcement ratios.

The names attached to each beam tested under fatigue loading are indicative of the loading and reinforcement conditions; for example, C80-20-0 is assigned to a beam reinforced with 2–10 M (10 M refers to Canadian standard hot-rolled reinforcing bar with cross-section area of 100 mm^2) and subjected to fatigue maximum and minimum loads of 80% and 20% of diagonal cracking load. The last value zero signifies 0.45% longitudinal reinforcement ratio. In the cases of beams C75-0-1 and C75-0-2, C75-0 signifies maximum and minimum fatigue loads of 75% and approximately 0%, respectively. The last numeral (1 or 2) represents 0.9% or 1.40% longitudinal reinforcement ratio, respectively.