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- Technical Paper -

FATIGUE BEHAVIOR OF RC BEAMS UNDER FIXED PULSATING AND MOVING LOADS

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ABSTRACT

Shear Fatigue behavior of RC beams with and without web reinforcement is investigated under different loading conditions on the basis of path and time dependent constitutive relations rooted in the multi directional fixed crack model for concrete. Both analytical and experimental investigations are conducted to quantify and compare the level of fatigue damage. The reduced fatigue life of beams under moving load and offset loading are discussed. A simple relation for the prediction of fatigue life under moving load is proposed for practical use on the basis of standard shear fatigue design equation of JSCE code, used for fixed fatigue loading.

Keywords: Fatigue, RC beam, RC Slab, shear transfer, moving load, Stress Reversal

1. INTRODUCTION

In General fatigue loading is of low intensity and high cycle structural problem. Each loading cycle is associated with small damage and the cumulative effect leads to final failure at service load. Thus, in dealing with the long term durability aspects of RC structures, fatigue is of importance as other durability problems. Past research suggests that, fatigue cracking can be a precursor to severe spalling, reinforcement corrosion and shear punching failure of concrete bridge decks [3].

Although fatigue life due to traffic movement on bridges is well known the resulting damage and its mechanism require further investigation. To date, several experimental and analytical studies have been conducted on RC slabs as well as beams [3], [4], [6]. These past studies provide important facts and behavioral understanding about fatigue problems. However, the clear mechanism and progress of damage due to fatigue is not fully understood yet, especially when it comes to a moving type of load. Besides, the analytical studies are commonly of empirical nature and lack generality. In consideration of versatility, path-dependent fatigue constitutive models for concrete tension, compression and rough crack shear are directly integrated with respect to time and deformational paths, on the basis of multi directional fixed crack model, to simulate the fatigue behavior of RC structures [1]. The rational of this analytical system lies in that any structural detail and loading pattern can be virtually simulated in a computer to estimate the fatigue life. The details of each fatigue constitutive model are described in-depth in [1], [2]. The reliability of the analytical system is verified for beams under a fixed type of loading and for slabs under both fixed and moving loads [1], [2]. In this study the authors use the same analytical system for the assessment of fatigue behaviors of RC slabs and beams under various loading conditions.

Moving load fatigue behavior of slabs may have a correlation with the fatigue behavior of RC beams. Experimentally it has been observed that the four way action in slabs is gradually transformed into two way action due to moving load. This may indicate the similarity of fatigue behavior of bridge decks and beams. One directional cracks in the transverse direction were also observed in prestressed bridges subjected to a moving type of load [8]. Therefore the authors try to investigate the fatigue damage mechanism of slabs by use of the fatigue behavior of beams subjected to a moving type of load.

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2. FATIGUE UNDER STATIONARY PULSATING AND MOVING LOADS

The fatigue life of RC slabs is highly reduced under moving load action as compared to that of the fixed pulsating load. Approximately 2-3 order difference is reported based on the experimental facts, [3], [4]. Similar result was also reported by 3D path dependent nonlinear computer analysis [2]. There is, however, a paucity of research, investigating the fatigue performance of RC beams under moving load, both experimentally and analytically. Thus, the authors try to examine the relative fatigue performance of RC beams subjected to stationary pulsating and moving load analytically by a 2D nonlinear FE analysis. A smeared crack approach with a multidirectional fixed crack modeling is adopted. In the analytical system, fatigue models for compression, tension and shear are installed [1]. For the purpose of investigation simply supported beams of span 2m with and without web reinforcement are considered, in which failure is governed by the diagonal shear. Details of the beam section are shown in **Fig. 1.** In the FE analysis 8-noded quadrilateral elements are used.

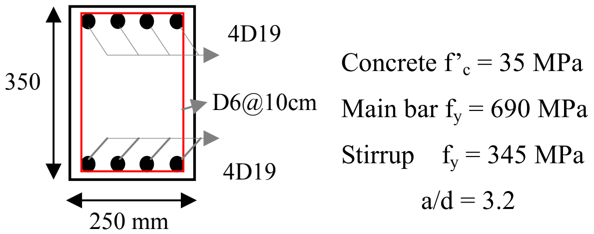


Fig1.Details of beam section with web reinforcement

2.1 Beams with Web Reinforcement

Figure 2 shows the experimental and analytical response of the beam with web reinforcement under static loading. The peak capacities for the experimental and analytical results are 331 kN and 339 kN respectively, indicating close agreement. The same beam is used for structural fatigue analysis and is subjected to a fixed pulsating and moving type loads at different stress levels. It should be noted that no-fatigue failure for web steel is considered in the analysis. It is intentionally neglected to clearly describe the fatigue deterioration of concrete, which is predominantly responsible for the fatigue degradation of RC structures. Accordingly, the analytical results are indicated in **Fig. 3.** In the analysis moving load is applied in such a way that, first 3 nodes on the most left upper side of the beam are loaded in 5 incremental sub steps. In the second step, the left most of the loaded nodes is unloaded, while a new node, adjacent to the right side of the loaded joints, is loaded simultaneously with equal increments. In this manner a constant load is made to move to the right most side and the same procedure is repeated for each cycle.

The mid span deformation pattern in the case of fixed fatigue loading is characterized by almost constant amplitude of vibration. On the other hand, in the case of moving load the amplitude gradually grows with the cycling of load. Unlike the case of fixed fatigue loading, the increase of residual deflection with the number of passages, for the moving load case, is quiet small as compared to the increase of peak deflection. At a stress level of 70 % the amplitude of vibration for the moving load is 1.3 times higher than that of the fixed fatigue loading. This large alternation of mid span deflection is an indicator for the higher damage progress in the case of moving load [3].

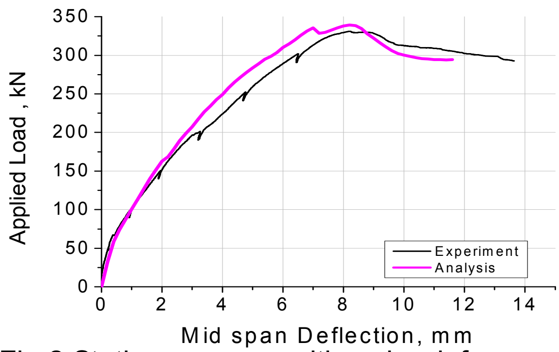
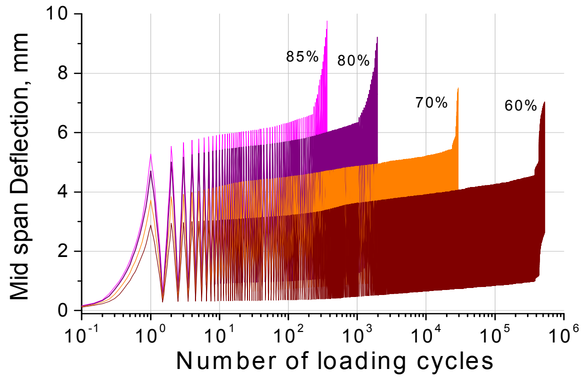
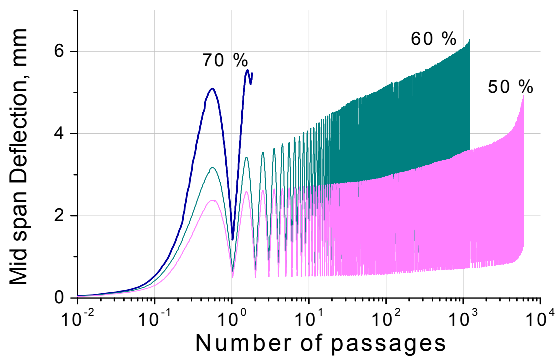


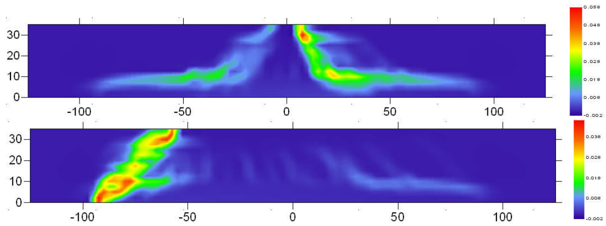
Fig.2 Static response, with web reinforcement



a) Response under fixed pulsating load



b) Response under moving load



c) Maximum principal strain distribution, fixed and moving Load

Fig.3 Fatigue response, Fixed and Moving load

A typical diagonal cracking close to the loading point can be seen for the fixed pulsating load. On the other hand, a diagonal cracking near the support is observed for the moving load, with extensive flexural cracks through the span, as shown in **Fig. 3c**. The difference is attributed to the variations of the ratio between applied shear force and shear capacity during movement of the load.

Based on the fatigue analysis results, the life at different stress levels are computed and the S-N diagram is plotted in **Fig. 4**. Where S represents the percentage of stress normalized by the fixed static capacity and N represents the number of cycles or passages to failure. The computed values based on FE analysis for the fixed fatigue loading are consistent with the standard JSCE design curve, proposed in [9]. The result shows that, the fatigue life under moving load is by nearly 2.5 – 3.0 orders lower than that of the stationary pulsating load. Similar results were experimentally reported for RC slab decks [3]. Yet, no experimental evidence has been reported regarding the fatigue life of simply supported RC beams under moving load.

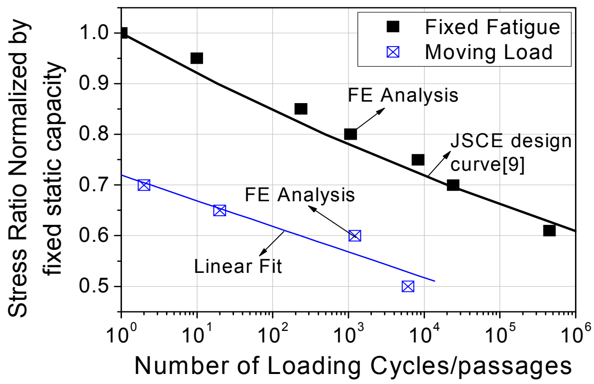


Fig.4 S-N diagram for beam with web bar

2.2 Beams with No Web Reinforcement

To examine the effect of web reinforcement similar analysis was done under fixed pulsating and moving load cases. The same beam was used except that the web reinforcement is removed. The computed S-N diagrams for both loading types are shown in **Fig. 5.** Consistently, the computed fatigue life values by the FE analysis are in reasonable agreement with the standard JSCE design curve. In other words, the S-N curve for the fixed fatigue loading case is less dependent on the shear reinforcement. The fatigue life under moving load is reduced by nearly two orders as compared to that of the fixed fatigue loading. This shows similar tendency with the case of the beam with web reinforcement but with reduced effect. Unlike the case of fixed fatigue loading the S-N diagram for moving load is influenced by the presence of web reinforcement. This means that, the effect of moving load may increase with the extent of shear cracks, thus indicating the importance of shear transfer fatigue under moving loads.

The maximum strain distribution under moving load shown in **Fig. 6**, unlike the case of beam with web reinforcement, is similar to the typical diagonal cracking in the case of static loading. This is due to the effect of web reinforcement. The shear contribution due the web reinforcement does not vary with the position of the load. This means, the critical shear ratio is close to the center rather than to the support position.

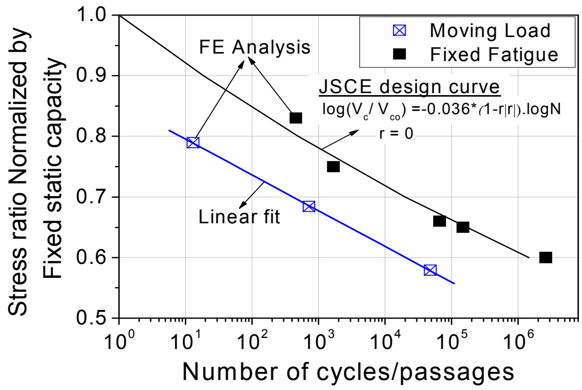


Fig.5 S-N diagram, beam with no web bar

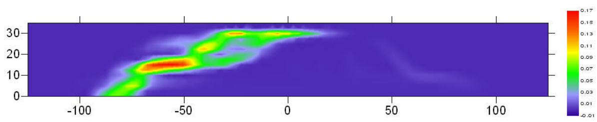
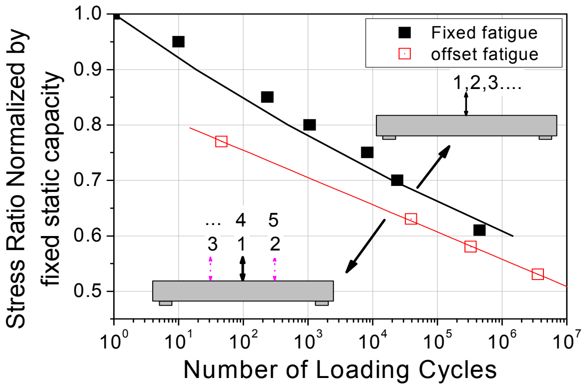


Fig. 6 Maximum principal strain distribution under moving load, no web reinforcement

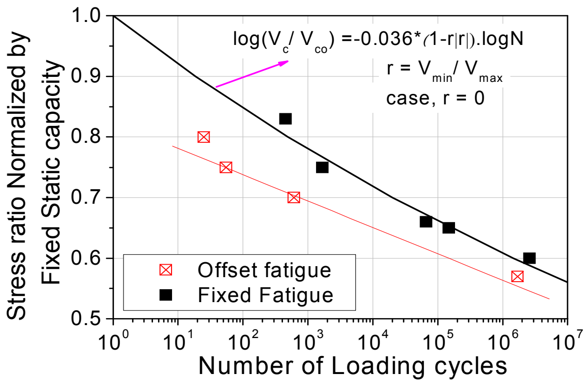
3. EFFECT OF OFF-SET LOADING

In practical situations, RC decks are subjected to traffic loading in a random manner. This random nature of loading may aggravate the degree of fatigue damage. Thus, a sensitivity analysis is conducted on beams with and without web reinforcement by applying an offset load alternating per cycle. First a full cycle is applied at the center of the beam. This is followed by the second and third load cycles of equal magnitude with an offset distance of 32.5cm from the center, to the left and right of the beam, respectively. This asymmetric nature of loading is supposed to create increased damage as compared to the fixed pulsating load.

The computed S-N diagram for the offset loading, as shown on **Fig. 7**, is observed to be lower by 1.0 – 1.5 orders as compared to the fixed fatigue loading. Hence, randomness of traffic loading may significantly influence the fatigue life of RC structures. At material levels fatigue damage becomes more critical if stress reversal is concerned. In the case of fixed fatigue loading, the stress path is of single sided nature. However, in the case of moving and offset fatigue loading, stress path vary in a reversed manner or single sided with larger amplitudes. The relative damage for shear transfer under reversed loading path is by 2- 3 orders higher than that of monotonic loading [5]. It is also reported that fatigue life is highly influenced by stress range or amplitude [6].



a) Beam with web reinforcement



b) Beam without web reinforcement

Fig.7 Effect of offset loading

The effect of offset distance was also investigated however no significant difference was observed in the range up to 50 cm. Similar tendency was observed in both beams with and without web reinforcement, except that, the effect of offset loading in the case of beam without web reinforcement reduces. This analytical fact indicates that, the effect of offset loading is highly pronounced at load levels close and above to the initiation of diagonal cracking. Noteworthy, the importance of offset loading for the fatigue life prediction of beams may have a substantial implication for bridge decks and is currently under discussion.

4. EXPERIMENTAL INVESTIGATION

These analytical investigations can serve as a basis of understanding the effects of loading patterns on the fatigue life. To verify the reliability of the analytically gained knowledge and understand the mechanism of damage an experimental investigation was conducted on a beam without web reinforcement. To observe the crack propagation mechanism in detail, the experiment was conducted under a step wise moving load. In one passage the beam is loaded at 5 different equally spaced points, each with an offset distance of 25 cm.

4.1 EXPERIMENTAL RESULTS AND DISCUSSION

The first loading is applied at the mid span with amplitude of 140 kN. During the first loading, only flexural cracks occurred. In the second loading, at an offset distance of 25 cm from the center, formation of diagonal cracking is observed. At the same time the flexural cracks beneath the loading point were extended slightly. In the third loading point neither new cracks nor appreciable extension of existing cracks were observed. Consequently, in the fourth loading point initiation of diagonal cracking was observed on the other half of the beam. During the fifth loading point most of the flexural cracks extended and the diagonal crack formed during the second loading point was extended as shown in **Fig. 8**. This indicates that, once a weak zone is formed, damage tends to accumulate on the previously damaged part due to other loading points. This effect is observed to be higher when the applied load is in the close neighborhood of the damaged zone. Lastly, the beam failed in the first loading point of the second passage, which is applied at the mid span. The already extended diagonal crack propagated and finally penetrated into the compression zone. No crack to crack interaction, [7], was observed in the whole loading process.

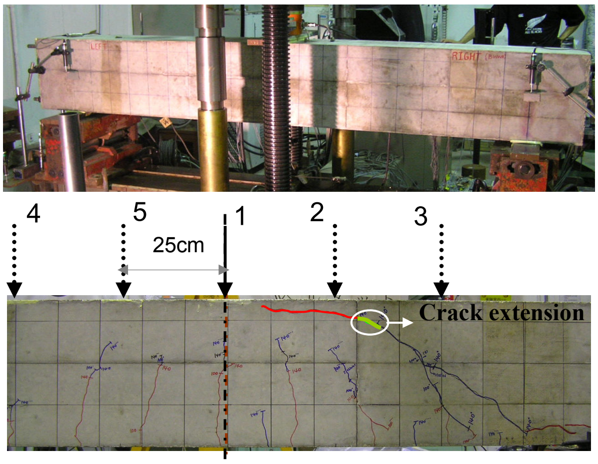


Fig. 8 Loading set up and Crack propagation at different loading points

The applied load (140kN) corresponds to, approximately 75% of the maximum capacity. If the same load level is maintained in a fixed pulsating manner at the mid span the expected fatigue life is more than 1000 cycles. This experimental fact partly verifies the reduced fatigue life of beams under moving load which was observed analytically. It is interesting to note that the experimental crack pattern at failure is similar to the one observed by the moving load analysis of beam with out web reinforcement, see **Fig. 6**.

One explanation for the reduced fatigue life of RC beams subjected a moving type load is due to the increase in actual stress ratio with the movement of the load. This is caused by the variation of shear capacity with the a/d ratio. However it should be noted that the history in the case of slabs is different. The reduced life in slabs is due the loss of punching shear capacity as a result of severe flexural cracking caused by moving load [3]. Stress reversal caused by the moving load is also a potential reason for the highly reduced life [3]. Additional effects such as loss of membrane forces could also be possible reasons.

In the case of slabs, extensive flexural cracks caused by moving loads may hinder the propagation of shear cracks. Consequently, a diagonal shear failure plane appears in the transverse direction normal to the traffic. However, moving load fatigue in RC beams is a 2D problem in which, the crack arrest mechanism in the longitudinal direction does not prevail. However, according to the current investigation, almost the same order of fatigue life reduction due to moving load, as in the case of RC slabs, is observed for RC beams too. This fact, indirectly suggests that, the shear transfer fatigue in the case of RC slabs has much to do with the reduced fatigue deterioration of RC slabs under moving loads. This fact is currently a point of interest and is under further scrutiny.

4.2 VERIFICATION OF EXPERIMENTAL RESULT

To verify the experimentally observed results, analysis was conducted with the same loading pattern. The experimental and analytical results are compared and the results are shown in **Fig. 9**. In the analysis the same load level as the experiment is used. Implicitly, the static capacity based on experiment and analysis is assumed to be the same. The analysis shows slight overestimation. In consideration of sensitivity of fatigue with the load level the analytical estimation is not far from the reality.

Figure 10 shows the maximum principal strain distribution based on analytical result. It can clearly be seen that, the experimentally observed crack pattern is well simulated by the analysis. Similar crack patterns were also observed in cut out sections of prestressed bridge slabs subjected to a moving type of load [8].

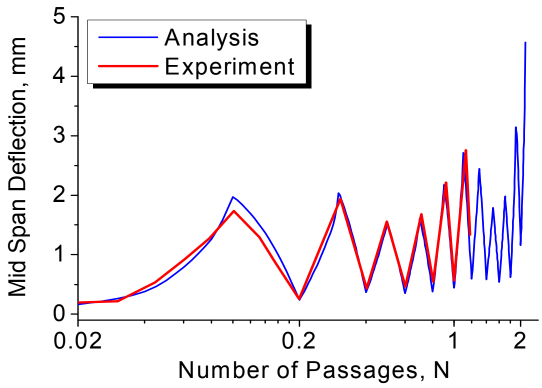


Fig. 9 Progress of Mid span deflection

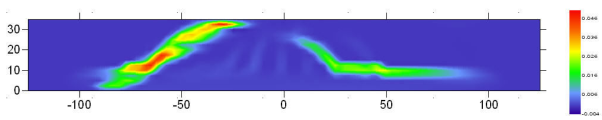


Fig. 10 Maximum Principal strain distribution

5. SIMPLIFIED SHEAR FATIGUE ESTIMATION UNDER MOVING LOAD

When a given beam is subjected to a moving load action, its behavior varies from shallow to deep beam. In other words the beam may act as shallow one when the load is close to the mid span and will act as deep one when the load is close to the support. Thus, although the apparent loading amplitude is 75%, in the considered beam, the actual stress ratio varies with the movement of the load. According to Niwa's Equation for shear design of beams, the maximum stress ratio occurs at some distance away from the center. It is then evident that fatigue at this point is more critical than at the center. This alternation of shear ratio during movement of the load could partly explain the reduced fatigue life under moving load in beams with a shear failure mode. Based on this idea, the shear fatigue life of RC beams could possibly be estimated based on the JSCE standard specification formula proposed by Okamura and Ueda (1982).

Therefore, if the maximum shear ratio is used rather than the apparent shear ratio at the mid span the computed S-N diagram reasonably agrees with the result obtained by FE analysis, as shown in **Fig. 11**. The remaining difference is attributed to the accumulated damages caused by the loads away from the critical section. For practical purposes the difference can be covered by using increased factor of safety, in the range 1.05 -1.06 for the stress level.

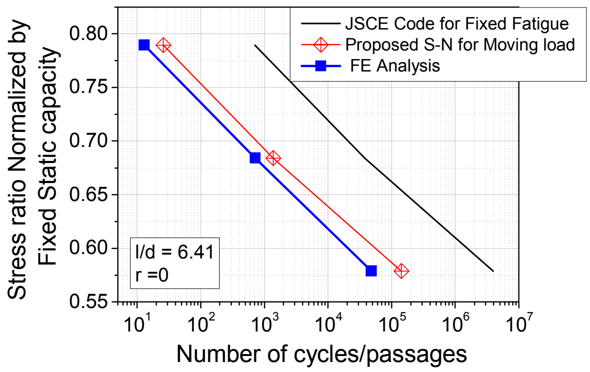


Fig.11 Proposed S-N diagram under moving load

6. CONCLUSION

The strong influence of loading pattern on the fatigue life has been pointed out for the beam as well as slabs. As in the case of slabs, 2 - 3 orders reduction in fatigue life was repeated due to moving load, compared to that of the fixed fatigue loading. Offset type of loading is also pointed out to significantly influence the fatigue life of RC beams. This means, a substantial influence for the case of slabs. The predominant role of shear transfer fatigue for the reduced life of RC slabs under moving load is emphasized. Based on the analytical and experimental investigations, a simple relation for the prediction of shear fatigue life of RC beams under moving load is proposed.

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