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Scientific paper

Shear Fatigue Simulation of RC Beams Subjected to Fixed Pulsating and Moving Loads

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Abstract

The fatigue behavior of RC beams subjected to moving loads is experimentally investigated. Analytical scrutiny is made on the shear fatigue behavior of RC beams subjected to moving loads based on strain path and time dependent fatigue constitutive models rooted in the multi-scale fixed four-way crack modeling of concrete. Moving load is found to cause dramatic reduction in fatigue life of RC beams as compared to that of the fixed pulsating load both in the experiment and analysis. The mechanism for the reduced fatigue life under moving loads in RC beams is discussed in contrast to that of RC slabs. A simplified 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. The effect of randomness in the position of loading is examined and its implication for the reliability of current fatigue life assessment method of RC members is put forward. The applicability of the multi-scale computational platform is verified for the fatigue investigation of RC beams subjected to moving loads.

1. Introduction

Engineering practice is always challenged with the innovations of new structures and construction technologies as engineers are obviously expected to come up with safe, rational and durable design proposals. Recently, there is also an increasing demand from society and organizations to know the life, performance and safety of their structures. On the other hand, there is a huge accumulation of knowledge on mechanics and modeling of concrete at multi-scale levels, as a result of intensive past studies. On this line, the advancement of computational mechanics is tremendously large. Given the above mentioned challenges in line with potential resources for their solution, the authors believe it is timely to develop and utilize the well established analytical technology used for static and seismic analysis to high cyclic structural problems.

Generally speaking, service loads are small enough to cause failure but they are sufficient enough to cause fatigue damage. Thus, when dealing with long term assessment and evaluation of RC structures it is indispensable to quantify the fatigue damage under repeated loading. Extensive studies have been conducted on the fatigue behavior of RC beams under fixed pulsating load.

Chang and Kesler (1958) and Taylor (1959) made one of the early contributions on the shear fatigue response of RC beams and pointed out the effect of load range and discussed on the different fatigue failure modes of beams without web reinforcement. Sabry and Okamura (1979) made extensive investigations on beams with and without web reinforcement. In their work, it is pointed out that stirrup strains increased in proportion to the logarithm of the cycles of repeated loading due to the decrease of shear force carried by concrete. Accordingly, they proposed the equation for the calculation of stirrup strain by applying the fatigue strength in shear of an identical beam without shear reinforcement to the decrease of shear force carried by concrete. Ueda and Okamura (1982) summarized the available studies and extended the works of Sabry (1979). In their work, an equation for the prediction of the shear fatigue life of beam without web reinforcement which includes the effect of load range is proposed. Currently, the proposed relation serves as a standard for shear fatigue life estimation of RC beams in JSCE code. These past investigations greatly contributed to current knowledge on the behavior of beams under fixed pulsating load. Yet, fatigue behavior of RC beams under moving load is not addressed, although it is well investigated for RC slabs (Maeda and Matsui, 1984).

To date fatigue investigation on RC structures is mainly based on empirical formulations. Although these formulations can provide important information for the life prediction of RC structures, they are less flexible as their formulation is based on specific parameters. In consideration of this Maekawa *et al.* (2006) proposed a direct path integral scheme for the fatigue assessment of RC structures, in which the fundamental mechanics of RC is implemented in the multi-scale four way fixed crack modeling frame work. Schematic representation of

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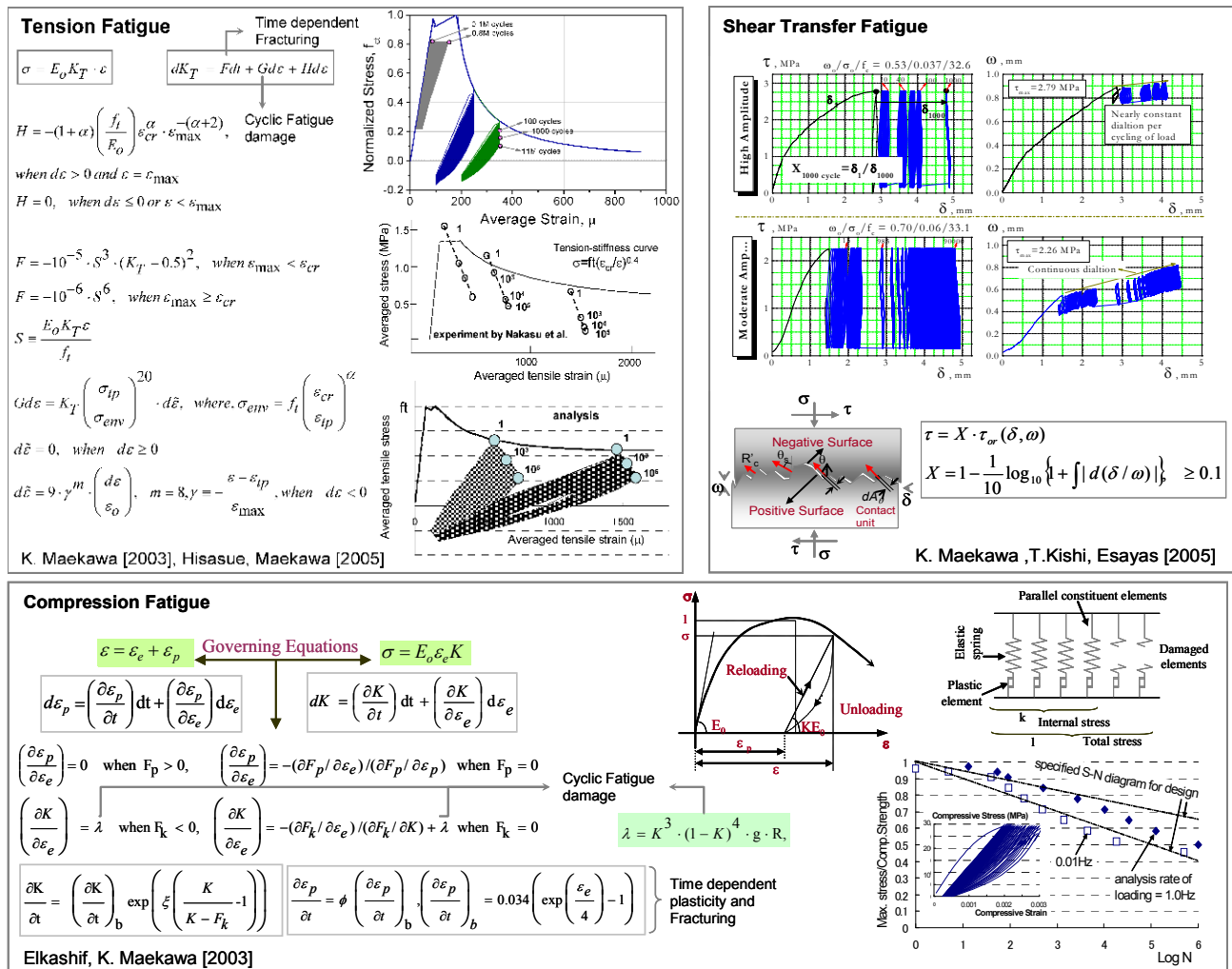
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the basic fatigue constitutive models in the analytical framework is presented in **Fig. 1**. Its applicability to the fatigue assessment of RC beams under fixed fatigue loading is verified. Furthermore, its applicability is confirmed in 3D analysis of RC slabs under both fixed pulsating and moving fatigue loads (Maekawa *et al.*, 2006). These facts show the rationale of the analytical tool and its advantage can be effectively utilized for the fatigue assessment of RC structures with varied range of parameters. In this study the authors attempt to check the applicability of the computational tool for the fatigue assessment of RC beams under moving loads. Noteworthy, the fatigue rupture of steel and reinforcement is intentionally ignored in the analytical frame work as the current target is to investigate the fatigue degradation of concrete.

Several investigations have been made on the moving load fatigue behavior of RC slabs. Matsui (1987), Perdikaris and Beim (1988) reported that, the fatigue life of RC slabs is dramatically reduced under moving loads, which is 2-3 orders lower than that of the fixed pulsating

load. Their work has greatly contributed to fatigue consideration of RC slabs in engineering practice. From the phenomenological point of view, moving load fatigue of RC beams is believed to be different as compared to that of the RC slabs. Generally speaking the mechanism of moving load fatigue in RC slabs is thought to be similar with that of fixed pulsating fatigue in RC beams, in which failure is observed to occur by diagonal cracking in the transverse direction to traffic. Unlike the case of fixed pulsating load, moving load in RC beams may cause large reversal of stress/displacement. Thus, behavioral understanding on the fatigue response under this large stress reversal is of interest from a mechanistic point of view.

The scope of this study is then, to examine the behavior of RC beams under moving load experimentally and analytically. For the mechanistic behavioral understanding of RC members subjected to high reversal of stress and to establish S-N relation of RC beams under moving load for practical use. Moreover, the authors try to identify important parameters and comment on the



Steel and Reinforcement bar Fatigue – Intentionally ignored

Fig. 1 Schematic representation of Tension, Shear and Compression Fatigue Constitutive Models.

current fatigue consideration of RC members analytically.

2. Experimental investigation on RC beam under step-wise moving load

To examine the effect of moving load on the shear fatigue mechanism of RC beams, an experiment on a simply supported beam without web reinforcement of span length 2m is considered. The beam consists of both tension and compression reinforcements. Based on the mid span loading, the shear span to depth ratio (a/d) is 3.2 with tensile reinforcement ratio of 1.47%. The geometric, material and cross-sectional details for the beam are shown in **Fig. 2**. As this study is mainly aimed to examine the shear fatigue mechanism, the beam is designed to fail in shear mode. The nominal shear capacity of the concrete is 95 kN in the analysis and is almost the same as the prediction by Niwa's shear capacity formulae (1987). The flexural yielding is estimated to occur at 220 kN of shear force, which is relatively higher than the shear capacity.

The beam is subjected to step-wise moving load, in which loading is applied on predefined points, to observe the crack propagation at different positions of the load. In one passage, the beam is loaded at five different equally spaced points, each with an offset distance of 25 cm. The first loading is applied at the mid span of the beam. In each loading step a constant load of 140 kN is maintained, which is in the range 75% – 80 % of the maximum shear capacity.

2.1 Reduced life and failure mode

Figure 2 shows the loading setup and crack pattern of beam. The first loading, amplitude of 140 kN, is applied statically with a loading rate of 0.2mm/ min. During this 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. 2**. 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 penetrated into the compression zone. No crack to crack interaction mechanism was observed during the whole loading process. While this observation is reasonable for the case

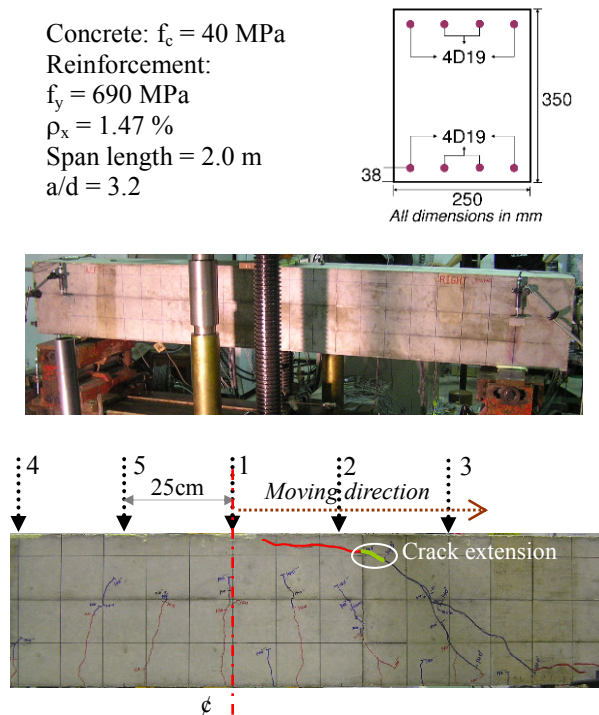


Fig. 2 Material and geometric details, loading set-up and crack pattern.

of beams it might not imply the same is true for the case of RC slabs.

The applied load (140kN) corresponds to, approximately 75%-80% of the maximum capacity. According to the experimental reports by Chang and Kesler (1958), Higai (1978) and Sabry (1979) the life for the same load level under fixed fatigue loading (at the mid span), is approximately 1000 cycles. Analytical results (Maekawa *et al.*, 2006) also reveal similar results. The computed fatigue life at different load levels, under fixed fatigue loading, is also presented in section 3.

This experimental fact partly indicates, the fatigue life of RC beams as well as RC slabs may be significantly influenced under moving load. At the considered load level nearly 3 order reduction in life as compared to the fixed pulsating load can be observed. Given this experimental fact, an analytical investigation is made by use of the multi-scale fixed four-way crack modeling of concrete based on strain path and time dependent fatigue constitutive models, to verify its applicability for the case of beams subjected to moving loads.

2.2 Verification of analytical model

The direct path integral scheme for fatigue simulation of reinforced concrete, summarized in chapter 1 (Maekawa *et al.* 2006), is verified with a wide range of experimental results, for RC beams under fixed pulsating load and RC slabs under both fixed pulsating and moving loads. In this section, the same computational platform is used to analyze the experimentally observed results for the

step-wise moving load discussed in section 2.1. The analysis is conducted by applying the same loading pattern and load level as the experiment. Implicitly, the actual static capacity is assumed to be the same as the analytically obtained result. Accordingly, the experimental and analytical results are compared and the results are shown in Fig. 3. The analytical result shows relatively slight overestimation. In consideration of sensitivity of fatigue with the load level the prediction by the analysis is not far from the reality.

Figure 3 shows the maximum principal strain distribution based on analytical result. It can be clearly 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 (Nakatani, 2002). Overall, the experimentally observed results are reasonably simulated by the analysis and this partly verifies the applicability of the analytical tool for the investigation of RC beams under moving loads.

3. Fatigue simulation of RC beams under fixed and moving Loads

This section targets to analytically examine the behavior and fatigue life of RC beams under moving load on the basis of the multi-scale fixed four-way crack modeling of concrete. For the purpose of investigation a simply supported beam of span length 2m is taken as a standard. Both beams with and without web reinforcement are examined. The shear span to depth ratio is 3.2 with main reinforcement ratio of 1.47% and shear reinforcement ratio of 0.25%. The geometric, material and cross-sectional details for each are shown in Fig. 4. The nominal shear capacity of the concrete is 99 kN. The shear capacity due to the web reinforcement, as estimated by the practical truss model, is 60 kN. The flexural yielding is estimated to occur at 220 kN of shear force, which is relatively higher than the shear capacities for each beam.

In the analysis a smeared crack approach with four way fixed crack modeling is adopted, in a 2D space. The mesh model is generated by quadrilateral elements with 8 nodes. Each fatigue constitutive models, (tension, shear, compression) rooted in the analytical platform are both strain path and time dependent (Maekawa *et al.* 2003, 2005). This important feature enables loading history and frequency effects to be taken in to account automatically.

3.1 Beam without web reinforcement

The beam is subjected to two types of loading, namely fixed pulsating and moving load. Fixed pulsating load is applied at the center of the beam with constant maximum load amplitude at a frequency of 1Hz, until failure. 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

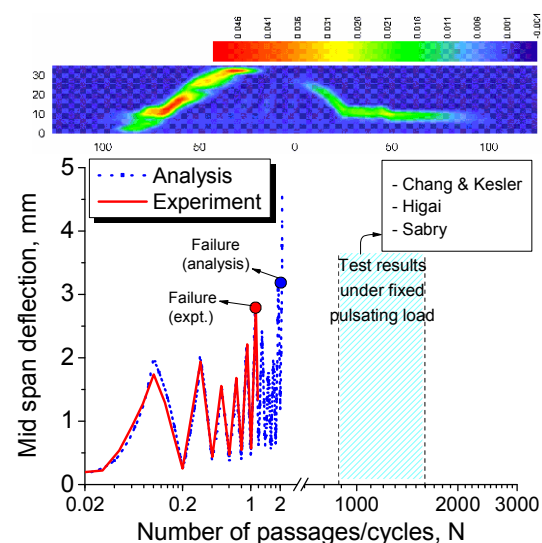


Fig. 3 Maximum principal strain distribution and progress of Mid span deflection with the number of passages.

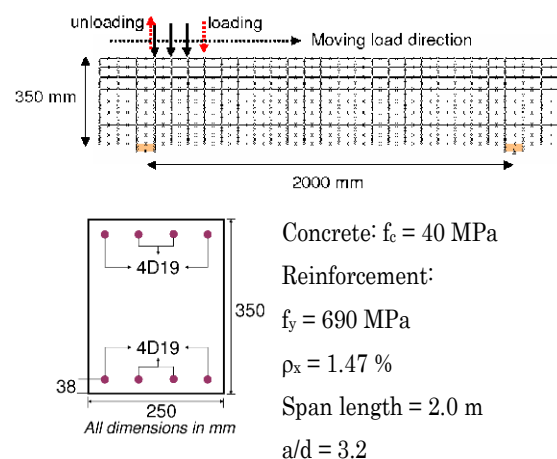


Fig. 4 Moving load, geometric and material details.

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, similarly the procedure is repeated for each cycle until failure. The moving load is applied in an effective contact length of 10 cm, with a speed of 7.2 km/hr. The speed is equivalent to 1Hz frequency of the fixed pulsating load. Thus time dependent effects for both types of loadings are similar. Each of the fatigue constitutive models summarized in chapter 1 are time dependent (Maekawa *et al.*, 2006) allowing loading speed effects to be taken in to account automatically.

Figure 5 shows typical responses of the progress of mid span deflection with the number of cycles for both fixed pulsating and moving loads, at different stress levels. The amplitude of mid span deflection for the same stress level is relatively large in the case of moving load; in fact similar observation is reported by Matsui (1987)

in case of slabs. In the study, the amplitude of the mid-span deflection for slabs is regarded as an indicator for the progress of damage. This may not be necessarily true for beams with shear failure mode, unlike the case of beams with bending failure mode.

Typical maximum principal strain contour plot for fixed pulsating and moving loads are indicated in Fig. 5. The crack patterns for both types of loading are similar, except that the diagonal shear crack in the case of moving load runs parallel to the compression reinforcement before failure, this is quite similar with experimentally observed crack pattern presented in section 2.1. In addition, the flexural cracks in the case of moving load are

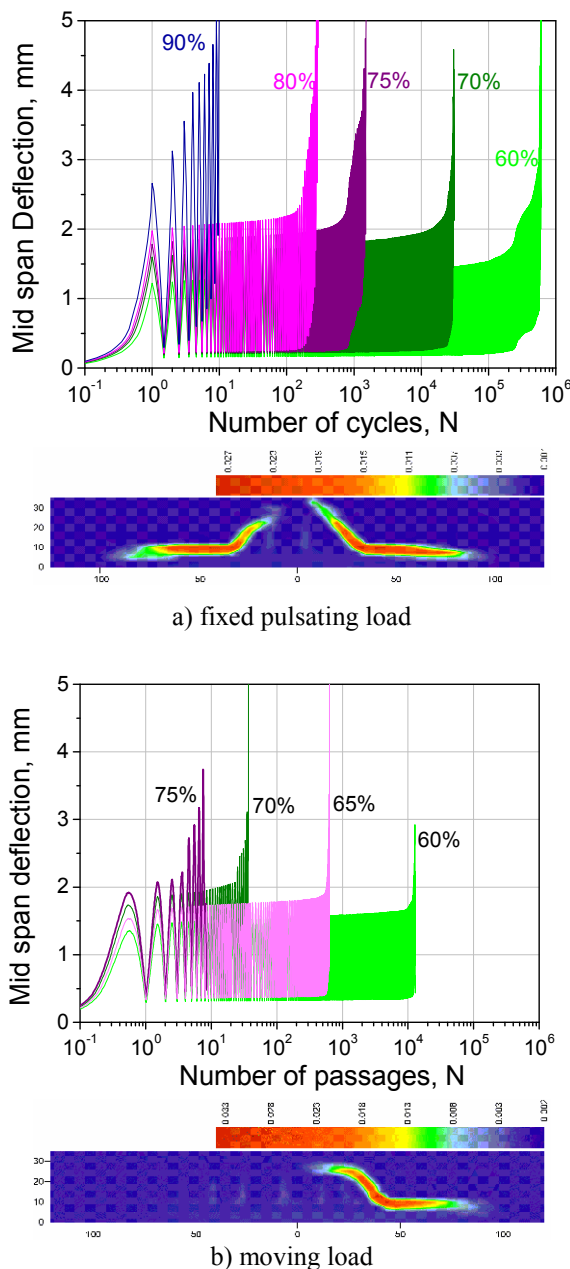


Fig. 5 Load-deflection relation and maximum principal strain contour plot, beam without web bar.

more extended to the compression zone and have no noticeable interaction with the diagonal shear crack.

Based on the fatigue analysis, the life at different load levels are computed and the results are summarized in S-N diagram, normalized by the computed static capacity.

Figure 6 shows the S-N curves for the case of fixed pulsating and moving loads. The computed S-N curve for the fixed pulsating load almost coincides with the shear fatigue design equation proposed, based on extensive experimental results, by Okamura and Ueda (1982). In contrast, the computed S-N curve for moving load case shows remarkable reduction in life, nearly by 2-3 orders, as compared to that of fixed fatigue loading. This is consistent with the experimentally obtained result under step-wise moving load (section 2.1). The effect of moving load is pronounced at higher stress levels. This can be explained by the fact that, effect of stress reversal is predominant at higher stress levels. Interestingly, the order of fatigue life reduction is similar to the fact observed by Matsui (1987) for the case of RC slabs.

3.2 Beam with web reinforcement

To investigate the effect of web reinforcement on the fatigue life of beams under moving load a beam with web reinforcement is examined. The same details as in the case of beam without web reinforcement are considered except for the web reinforcement of 0.25%. As the main focus in this study is directed on the fatigue degradation of concrete, which is predominant in the case of RC structures governed by shear, the authors intentionally ignore the fatigue rupture of web reinforcement. Indirectly, the reduction in shear resistance due to concrete is taken by the increase in strain of stirrups.

Figure 7 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. Prediction of the static capacity based on the practical truss model is around 308 kN. The difference may be attributed to the basic assumption of the truss model.

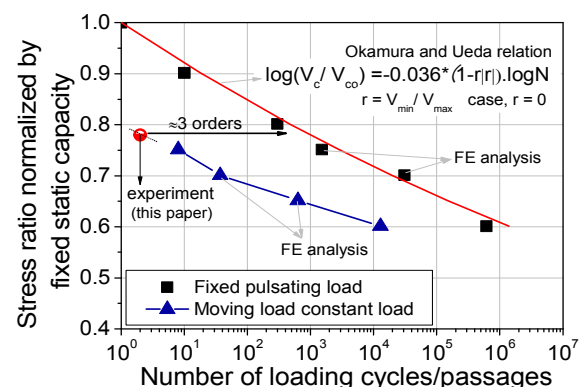


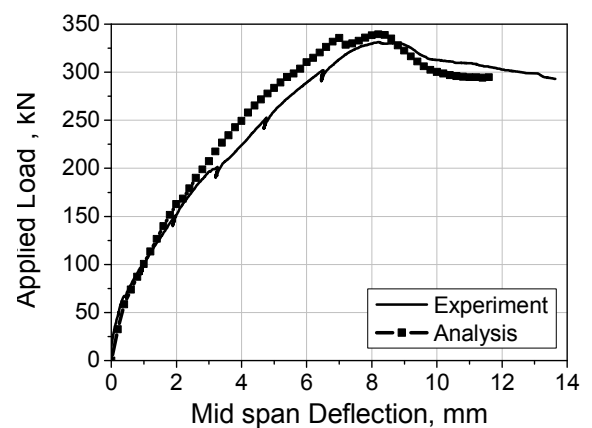
Fig 6 S-N diagram for fixed pulsating and moving loads, beam without web reinforcement.

Figure 7b, c show the progress of mid-span deflection with the number of loading cycles and typical maximum principal strain contour plot for the respective types of loading. Like the case of beam without web reinforcement; the amplitude of mid span deflection under moving load is higher. In contrast, the rate of increment of the amplitude is large for the beam with web reinforcement. Unlike the case of beam without web reinforcement, here the diagonal crack under moving load occurs near the support position. The difference is attributed to the variations of the ratio between applied shear force and shear capacity during movement of the load. When the load moves along the span of the beam, its behavior fluctuates from shallow to deep one. For the case of beam with web reinforcement the critical shear location shifts towards the support position due to the invariability of the shear contribution by the web reinforcement with the movement of the load.

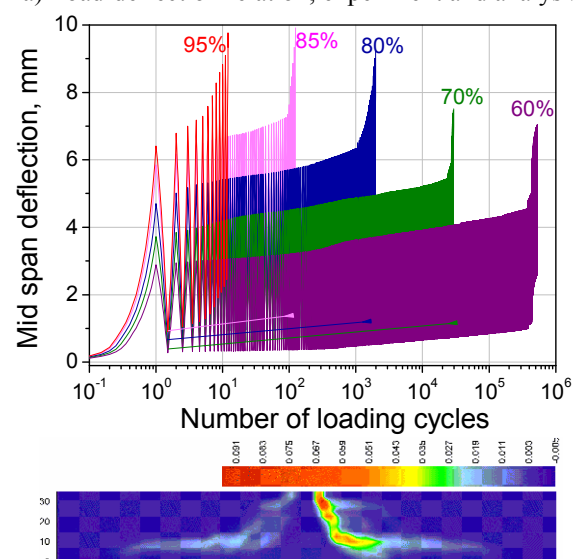
Figure 8 shows the S-N curves for both types of loading, the computed curve for the fixed pulsating load is close to the shear fatigue design equation proposed by Okamura and Ueda (1982) with reasonable accuracy. The S-N curve for the moving load also shows dramatic reduction in life with relatively pronounced effect as compared to that of beam without web reinforcement. This difference may indicate the significance of shear transfer fatigue on shear cracks.

Overall, the above facts indicate that fatigue life in beams is reduced by 2-3 orders, under moving load as compared to the fixed pulsating load. Although, the order of reduction is similar to that reported in the case of slabs (Matsui, 1987) the mechanisms for the reduced life are not the same. Shear behavior of beams is strongly influenced by the shear span to depth ratio, unlike that of slabs. As a result, a constant moving load does not really represent a constant shear force to capacity ratio. In other words, if the moving load is applied in such a way that, the shear force to capacity ratio is kept constant, the fatigue life may tend to be closer to that of the fixed pulsating load. Thanks to the advancement of computational mechanics, currently this type of loading can be simulated on analytical basis, though practically it is not easy to conduct such kind of experiment. In the analysis a constant shear force to shear capacity is maintained by varying the magnitude of the load with the movement away from the mid span of the beam, according to the shear capacity relation proposed by Niwa *et al.* (1987).

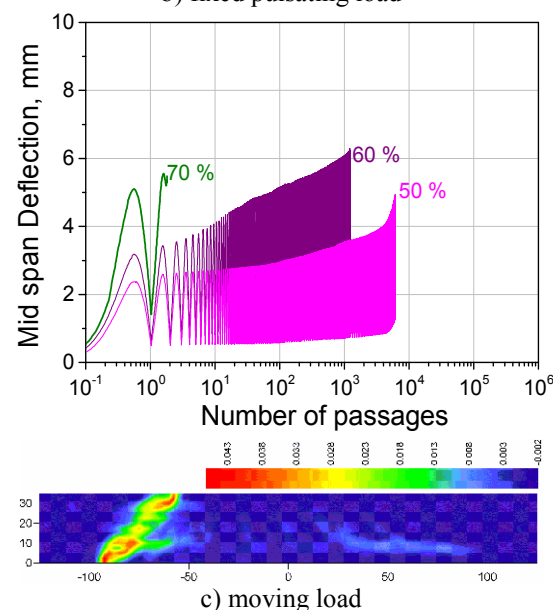
Figure 9 shows the S-N curve for the constant shear ratio as compared to that of fixed pulsating load. It is interesting to note that, the fatigue life tends to approach to that of the fixed fatigue loading at lower stress levels. Implicitly, the reduced fatigue life of beams under moving load is partly due to the combined effects of stress/displacement reversal and variation of shear force to capacity ratio at each section. In fact, moving load induces not only reversed stress path but also larger stress amplitude paths. Stress reversal is primarily predominant at higher stress range near to the initiation of diagonal



a) Load-deflection relation; experiment and analysis



b) fixed pulsating load



c) moving load

Fig. 7 Load-deflection relation and maximum principal strain contour plot, beam with web bar.

crack. On the other hand, at lower stress levels the fatigue life is governed by the combined effects of stress/displacement reversal and variation in the shear force to shear capacity ratio during the movement of the load.

3.3 Mechanism of moving load fatigue in RC beams (compared to that in Slabs)

The primary reasons for the reduced fatigue life of RC beams under moving load are; due to the relatively large

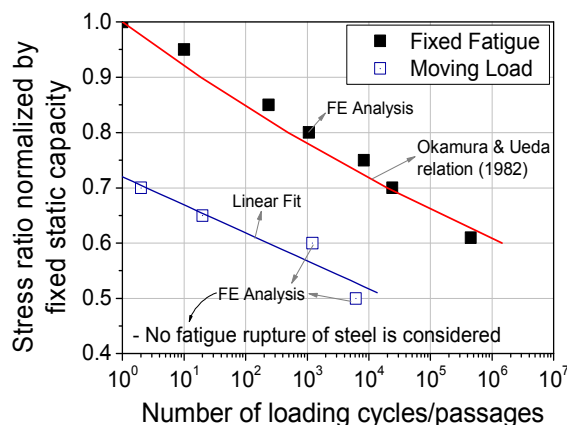


Fig. 8 S-N diagram for fixed pulsating and moving loads, beam with web reinforcement.

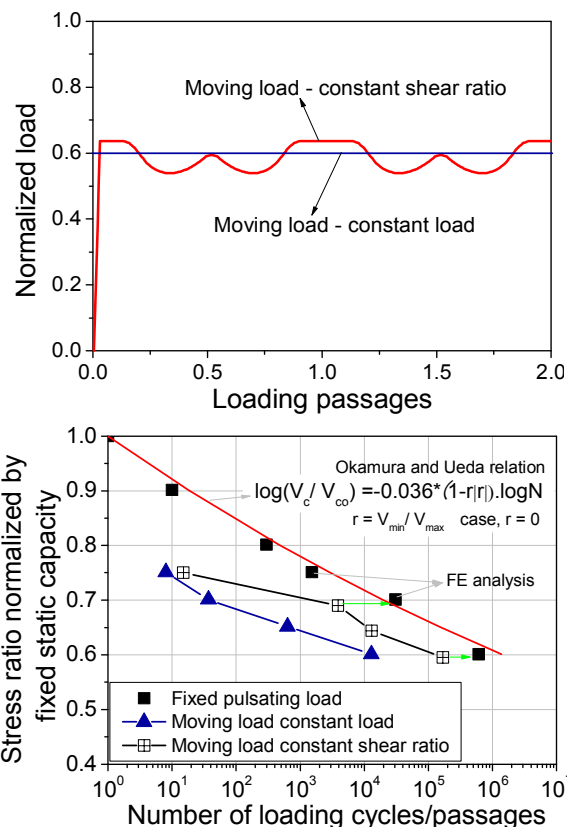


Fig. 9 a) load profile for shear constant ratio b) S-N diagram for loading under constant shear ratio.

stress reversal caused by the movement of the load and the increase in actual stress ratio caused by the movement of the load. The later is caused by the variation of shear capacity with the a/d ratio. The relative influence of stress reversal becomes predominant with the initiation of diagonal cracks. With the movement of the load the shear cracks are subjected to repeated displacement reversals. Shear transfer fatigue under displacement reversal is reported to cause dramatic reduction in life, nearly by 2-3 orders, as compared to that without reversal (Gebreyouhannes *et al*, 2005). The accelerated reduction in shear transfer is accompanied by further extension of the diagonal crack. This in turn creates high compressive stress on the uncracked portion of the section. As a result, the inclination of the crack becomes more of horizontal and runs parallel to the compression bar before the penetration of the compression zone.

The mechanism of moving load fatigue in the case of RC slabs is thought to be different as compared to that of RC beams. According to the past investigations, the reduced life in slabs is due the loss of punching shear capacity as a result of severe flexural cracking caused by moving load (Matsui, 1987). Stress reversal caused by the moving load is also a potential reason for the highly reduced life (Matsui, 1987). 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 in the longitudinal direction. The reversal of cyclic shear force along the extended flexural cracks largely reduces the stress transfer in the longitudinal direction. Hence, the slab acts no more as a slab rather as discrete beam elements. Consequently, the moving load acts in a similar manner as a fixed pulsating load for the beam-slab elements, thus a diagonal shear failure plane appears in the transverse direction only normal to the direction of traffic.

Moving load fatigue in RC beams is a 2D problem in which, the crack arrest mechanism in the longitudinal direction most likely does not prevail (section 2.1). Moreover, unlike slabs the fatigue life of RC beams is influenced by the variation of shear span to depth ratio caused by the movement of the load. 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. These facts, indirectly suggest that, the shear transfer fatigue could be the primary reason for the reduced fatigue life of RC slabs under moving loads. To reinforce the potential implications of this study for the case of slabs, further scrutiny is required.

4. Simplified shear fatigue life estimation under moving load

As explained in the previous sections, 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, depending on the span length and effective depth of the beam. Thus, the apparent loading amplitude ratio (applied load normalized by central load static capacity) is not necessarily the governing load to capacity ratio, as the actual shear force to capacity ratio varies with the movement of the load. According to Niwa's Equation for shear design of beams (1987), the maximum stress ratio occurs at some distance away from the center. It is then evident that fixed fatigue at the point of maximum shear stress ratio is more critical than at the mid span.

This alternation of shear ratio during movement of the load is mentioned as one reason for the reduced fatigue life of RC beams under moving load with a shear failure mode. Accordingly, the shear fatigue life of RC beams could possibly be estimated based on the JSCE standard specification formula proposed by Okamura and Ueda (1982). For a given beam, the maximum shear ratio can be expressed as a function of the apparent shear ratio and length to effective depth ratio, as shown in Fig. 10. Thus, the predicted S-N diagram based on the maximum shear ratio reasonably agrees with the result obtained by FE analysis, as shown in Fig. 10. The 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.

5. Is the current practical assessment of fatigue life reliable?

The idea that stress/displacement reversal plays an important role to the fatigue deterioration of RC members may indirectly imply, asymmetric type of loadings could beget more pronounced fatigue damage. Current fatigue assessment of RC members is based on fixed pulsating load at mid-span for beams or moving load at the central axis for slabs. However these loading positions may not be the critical ones as far as fatigue is concerned. As a matter of fact, in practical situations, RC decks are subjected to traffic loading in a random manner. This random nature of loading may further aggravate the degree of fatigue damage.

Analytical investigation 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 which is equivalent to one passage at the central axis in slabs. This is followed by the second and third full loading 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, herein after offset loading, is supposed to create increased damage as compared to the fixed pulsating load. Figure 11 shows the computed S-N diagram for the offset loading as compared to fixed pulsating load. The life for the offset loading is observed to be lower by

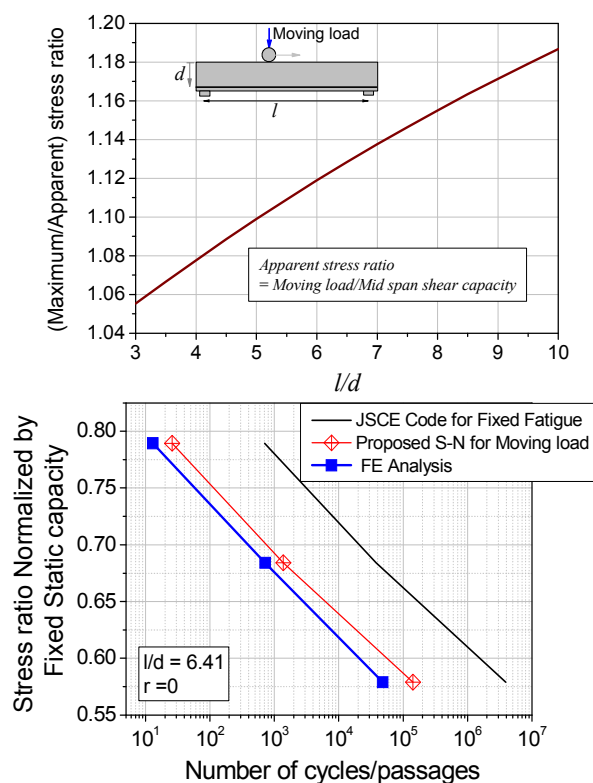
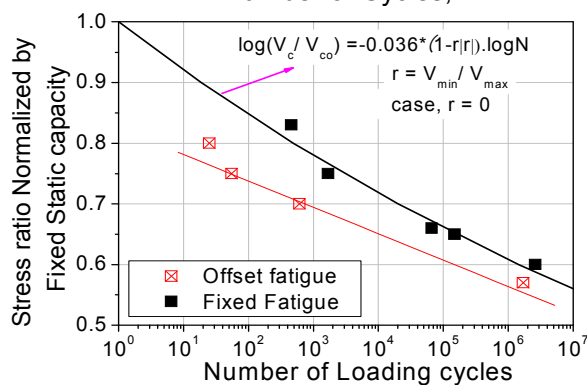
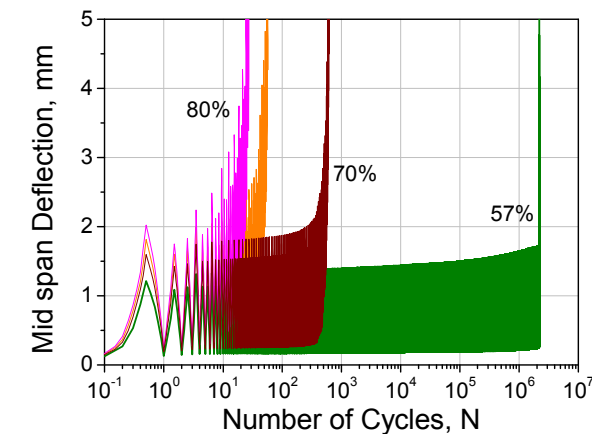


Fig. 10 S-N diagram base on simplified shear fatigue estimation method as compared to FE analysis.

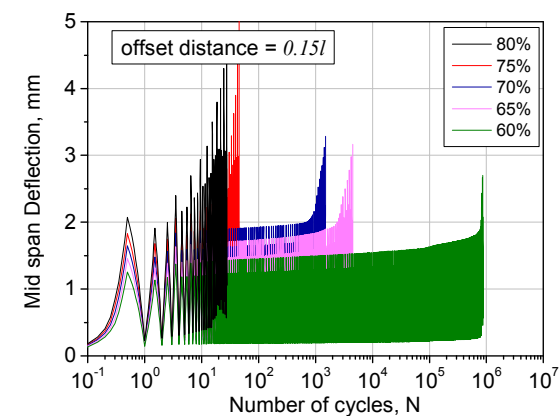
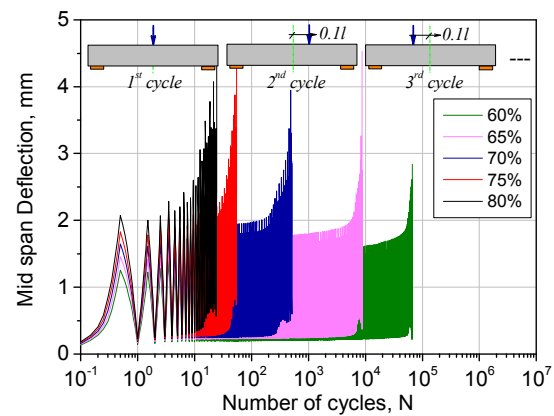
1.0 – 1.5 orders for both beam with and without web reinforcement. The reduction in life is dependent on the offset distance and magnitude of the applied stress level. The effect is highly pronounced at higher stress levels due to increased effect of shear displacement reversal. To investigate the effect of offset distance, loading at different values, $0.0l$, $0.1l$, $0.15l$ and $0.25l$ is examined.

Figure 12 shows the S-N diagram for each values of offset distance. It can be seen that there exists a critical distance from the center of the beam at which the fatigue life is largely reduced. This position is close to the mid span of the beam, approximately at a distance of $0.11l$ - $0.15l$ from the center of the beam. If the offset distance is large (greater than $0.2l$) no pronounced effect to the fatigue life can be seen rather it tends to increase the fatigue life. This indirectly implies that, loading points at a relatively far distance from the neighborhood of the critical position have less significance to the fatigue life.

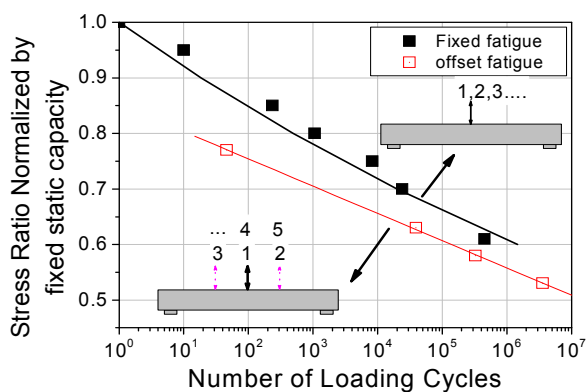
Overall, randomness of traffic loading may significantly influence the fatigue life of RC structures. At material levels fatigue damage becomes more critical if stress reversal is concerned. In the case of fixed fatigue loading, the stress path is of single sided nature. However, in the case of moving and offset fatigue loading, stress path vary in a reversed manner or single sided with larger amplitudes. According to material level experimental investigations, the relative damage for shear transfer



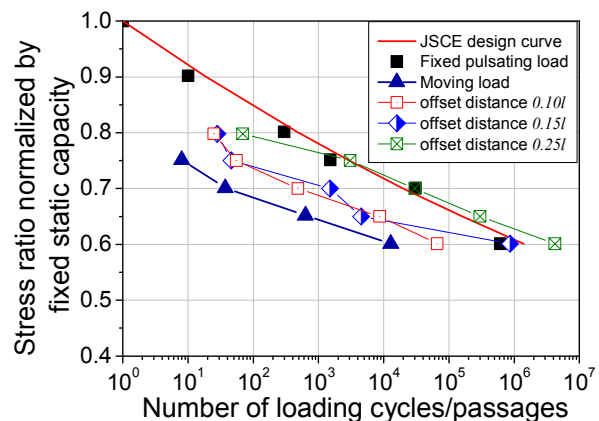
a) Beam without web reinforcement



a) Load-deflection relation at 0.11 & 0.15l offset distance



b) Beam with web reinforcement



b) S-N relation for different offset distance

Fig.11 Effect of offset loading.

Fig.12 Effect of offset loading with loading distance.

under reversed loading path is by 2- 3 orders higher than that of monotonic loading (Gebreyouhannes *et al*, 2005). Similarly, tension and compression fatigue is reduced by nearly 2 orders when stress reversal is concerned. It is also reported that fatigue life is highly influenced by stress range or amplitude (Cornelissen, H. A. W. and Reinhardt, H. W., 1984).

6. Effect of pre-Induced vertical cracks to the fatigue performance

Concrete is an isotropic material with a relatively much higher compressive strength than its tensile strength. Its low tensile strength makes it susceptible to early age cracking caused by excessive shrinkage and/or thermal

effects. Thus cracks can easily be generated in RC members due to past loading and environmental attack. These cracks generally have a variety of widths and orientation and can influence the structural behavior of RC members. The influence of precracks on the shear response of RC beams under static loading is reported by Pimanmas and Maekawa (2001). Accordingly, RC beams with vertical pre-cracks show considerably higher shear capacity and reduced stiffness as compared to non pre-cracked one. The increase in shear capacity is attributed to the crack to crack interaction mechanism between the new and existing cracks as illustrated in **Fig. 13**. Given the mechanistic understanding of crack to crack interaction under static loading, further investigation is required to check the viability and effect of the mechanism for cyclic loading paths.

The reduced stiffness of precracked beams suggests that, the amplitude of the midspan deflection for pre-cracked beam is larger as compared to sound one, at least for the beginning few loading cycles. It has been reported that, the amplitude of the midspan deflection is an indicator for the progress of fatigue damage (Matsui, 1987). Accordingly, it may be supposed that the fatigue life of precracked beams may be lower. On the other hand it is also argued that the higher amplitude value does not necessarily indicate lower fatigue life especially when the failure mode is in shear. Hence, it is of interest to get an insight on how pre existing cracks influence the fatigue behavior of RC members. The mechanics of shear anisotropy which governs the activation or dormancy of cracks in an element with multi-cracks is rooted, in the analytically frame work (Pimanmas and Maekawa, 2001). Thus based on this mechanics rationale, the effect of pre-induced cracks to the fatigue life is analytically investigated.

A beam with vertical pre-cracks is subjected to a fixed pulsating and moving load fatigue. The pre-cracks are introduced by initially applying an axial force of 540 kN and then fully unloading the beam. The computed static capacity of the pre-cracked beam is observed to be higher by 11% as compared to the sound beam. The relative

increase in capacity due to the presence of the pre-cracks is small as compared to that reported by Pimanmas and Maekawa (2001) 40 – 60 %. This is because the applied axial load level is quite low as compared to the yield level of reinforcement bars, thus resulting in small opening of the precracks upon unloading.

Figure 14 and **15** show typical fatigue response and computed S-N diagram for both sound and pre-cracked beam under fixed pulsating and moving loads. The progress of mid span deflection with the number of loading cycles at a load level of 60% is indicated for both types of loading. At this load level, the amplitude of mid span deflection for the pre-cracked beam is higher by 20-30% than that of sound beam. On the other hand, the fatigue life for the pre-cracked beam is longer by nearly one order as compared to that of the sound beam for fixed pulsating and moving load. The increase is due to the fact that, the formation of diagonal shear crack is delayed by the relaxation due to shear slip at the pre-cracks. At higher stress levels the effect of pre-cracks is seen to adversely affect the fatigue life because majority of the anisotropic shear slip is mobilized during the first load cycle and no relaxation of stress concentration can be realized in the subsequent cycles.

All in all the fatigue behavior of pre-cracked beams as compared to sound ones is a close manifestation of their relative responses under static loading. The increased fatigue life due to the presence of vertical pre-cracks has important implication for the failure mechanism of slabs under moving load. In the case of RC slabs, vertical cracks transverse to the direction of traffic are created due to combined effects of environmental effects and loading. The formation of these cracks may delay the formation of diagonal cracking in the longitudinal direction; thereby, changing the failure mode from radial type to a two dimensional shear fracturing in the transverse direction.

7. Conclusions

Shear fatigue behavior of RC beams subjected to fixed pulsating and moving loads is analytically investigated based on strain path and time dependent fatigue constitutive models rooted in the multi-scale fixed four-way crack modeling of concrete. Accordingly the following main features are pointed out:

Based on the experimental and analytical investigations, the fatigue life of RC beams under moving load is remarkably reduced, and is 2-3 orders lower than that of fixed pulsating load. This dramatic reduction in the fatigue life of RC beams under moving load is due to the combined effects of stress/displacement reversal and variation in shear force to capacity ratio.

The applicability of the computational tool based on the direct path integral scheme is further verified for the fatigue assessment of RC beams under moving load; and is able to simulate the experimentally observed cracking pattern and reduced fatigue life.

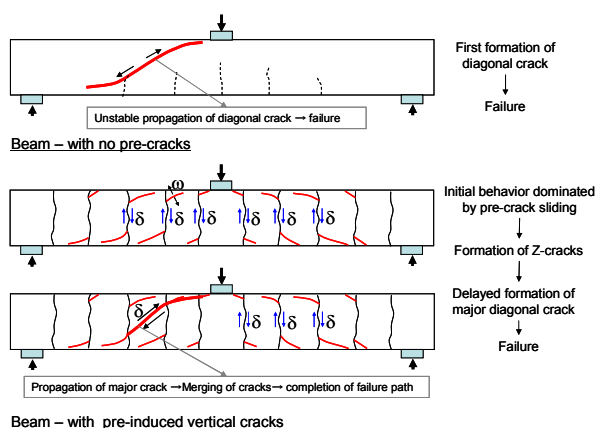


Fig. 13 Shear failure mechanism of pre-cracked beams.

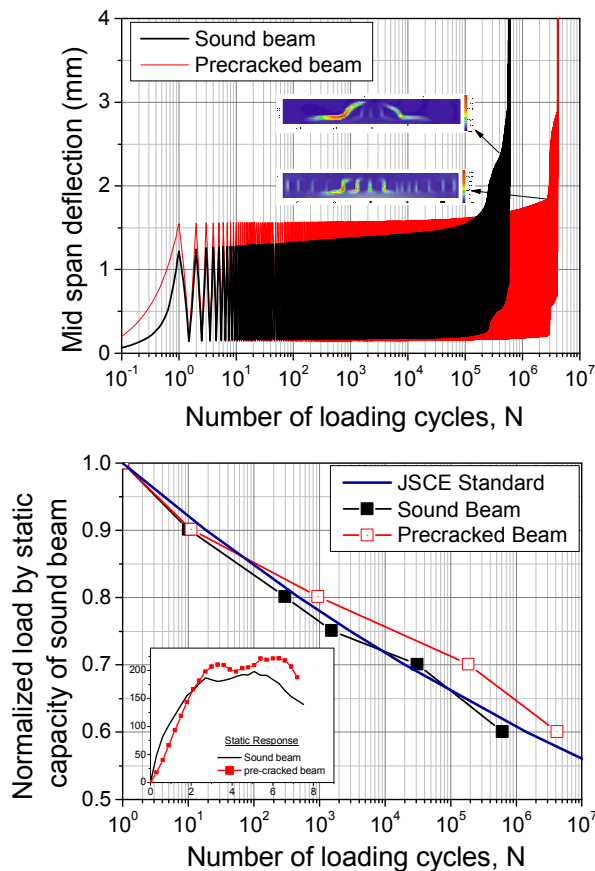


Fig. 14 a) Load-deflection relation b) S-N diagram for pre-cracked beam, of pre-cracked beam as compared to sound beam, fixed pulsating load.

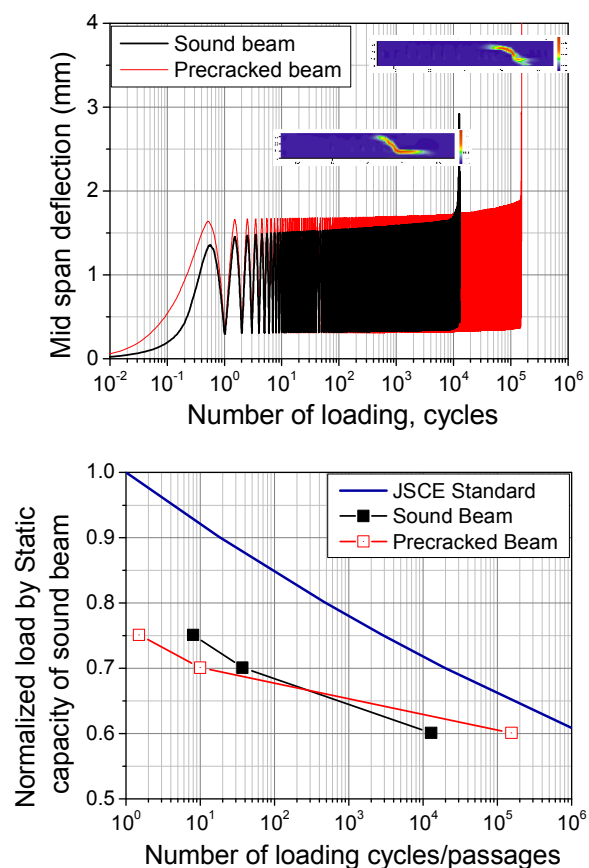


Fig. 15 a) Load-deflection relation b) S-N diagram for pre-cracked beam, of pre-cracked beam as compared to sound beam, Moving load.

Based on the analysis, a simple relation for the prediction of fatigue life under moving load is proposed on the basis of the standard shear fatigue relation of JSCE, for practical use.

The importance of randomness in traffic load to the fatigue life is examined analytically. Asymmetric type of loading is found to significantly reduce the fatigue life as compared to central-axis based loading. Thus, fatigue life prediction based on the central-axis loading may lead to unsafe results. To exemplify this fact experimental verification is required.

The delay of diagonal crack formation due to the presence of pre-cracks is indicated to be a viable mechanism even under high cyclic loading. The fatigue life of RC beams with precracks is observed to increase as compared to sound beam both under fixed and moving loads.

It is focused that, computer based simulation based on rational modeling of concrete (RC) can serve as a key tool for the long term evaluation and behavioral understanding of RC members.

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