Fracture Mechanics Based Fatigue Analysis of RC Bridge Slabs Failed in a Punching Shear Mode under Cyclic Moving Load

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1. INTRODUCTION

Around the world, a brittle and catastrophic punching shear failure of the RC deck slab has been commonly observed due to the overlooks of a shear capacity in previous design codes. A large amount of researches have been conducted on a fatigue punching shear failure of RC bridge slabs experimentally, empirically and numerically over the last few decades. However, the empirical methods cannot reflect the inner degradation mechanisms as in Maeda and Matsui (1984), and the numerical approaches are very time-consuming as in Drar and Matusmoto (2016). Therefore, it is of great significance to innovate an efficient and sophisticated fatigue analysis method considering dominant degradation mechanisms of RC bridge slabs under cyclic moving loads.

In this study, a theoretical fatigue analysis method is proposed for an RC slab under cyclic moving loads. The applicability and reliability of the method are confirmed with encouraging results from a comparison with experimental results and existing empirical equations. In addition, compared with existing methods, this method can not only account for the degradation mechanisms but also achieve time-saving (1-2 hours/load which is only a small percentage of that for numerical methods).

2. PROBLEM FORMULATION

2.1 Problem simplification

For an RC slab under cyclic moving loads, an empirical life prediction equation was formulated with the punching shear capacity of a critical RC beam as the only parameter used in Maeda and Matsui (1984), which indicates that the fatigue life of the RC slab depends on the fatigue life of the critical beam. Geometries of the critical RC beam are shown in Fig. 1, where l_w and b are the length and width of the wheel/beam contact area; d_e is the distance from the centroid of tensile rebars to the beam upper surface; b' should equal to d_e as reported in Maeda and Matsui (1984). Therefore, in this study, the life prediction of an RC bridge slab is simplified into the life prediction of a critical RC beam focusing on the propagation of punching shear cracks along 45° lines symmetrical with respect to the moving load as shown in Fig. 1.

2.2 Formulate sectional stresses and forces with cracking state parameters

For the critical RC beam subjected to general loads, sectional stresses and forces acting on the punching shear crack cross section are shown in Fig. 2. To determine all the sectional forces and stresses in Fig. 2, three widely employed assumptions are employed as follows: (1) plane cross-section assumption; (2) the cracked cross-section is assumed to rotate around a neutral axis; (3) linear crack opening profile assumption. Based on these assumptions, strains of all materials and the crack opening displacement (COD) profile are expressed with α, β and crack mouth opening displacement (CMOD, δ). α, β and δ are named as cracking state parameters in this study. With the obtained material strains and COD profile, reaction stresses from all components can be expressed with α, β and δ following some appropriate material stress-strain models and a concrete bridging model. To account for a multi-crack effect and a bond slip effect, the rebar stress-strain relation is modified accordingly. From 2nd loading cycle to final failure, structural degradation is considered through introducing a concrete bridging degradation model and a bond slip degradation model.

2.3 Governing equations with cracking state parameters

In order to determine α, β and δ after every loading cycle, three independent equations, i.e. force equilibrium equation along y axis, moment equilibrium equation and CMOD decomposition equation proposed in Deng and Matsumoto (2017a, b), are formulated with α, β and δ in this study.

2.4 Failure moment determination with cracking state parameters

In this study, the shear capacity is assumed from the shear strength of concrete and the dowel action of flexural rebars. However, as the formed cracks are polished by the repeated opening and closing process, the shear resistance from cracked concrete is ignored. In addition, as a delamination along the upper rebars was observed in tested specimens, the dowel effect of upper rebars should be excluded after the crack tip reaching upper rebars. According to these considerations and following AASHTO and ACI equations, the punching shear capacity can be related to the cracking state parameters. Correspondingly, the failure moment is determined with this capacity in this study.

3. NUMERICAL RESULTS AND EXPERIMENTAL VERIFICATION

In this study, to investigate the applicability and reliability of the proposed method, a fatigue analysis based on this method is conducted on an RC slab (C0) reported in Mitamura et al (2012). This slab was tested by Civil Engineering Research

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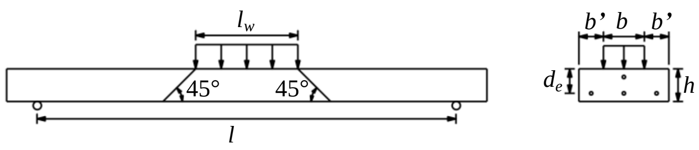


Fig. 1 Geometry of the simplified RC beam

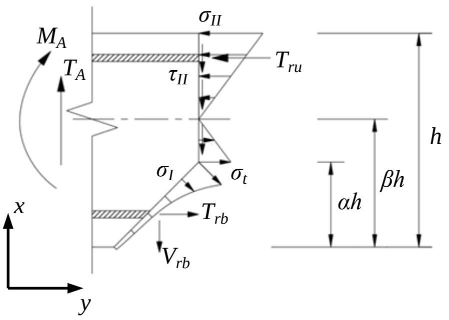


Fig. 2 Sectional stresses and forces

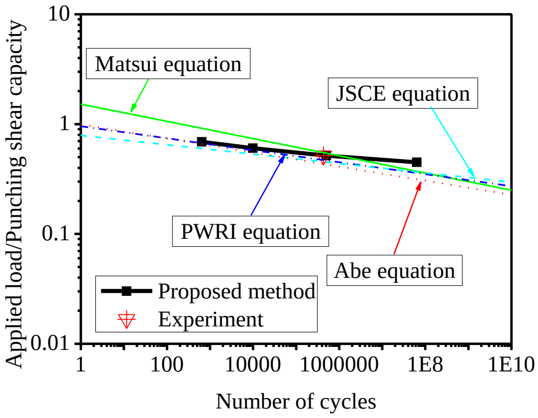
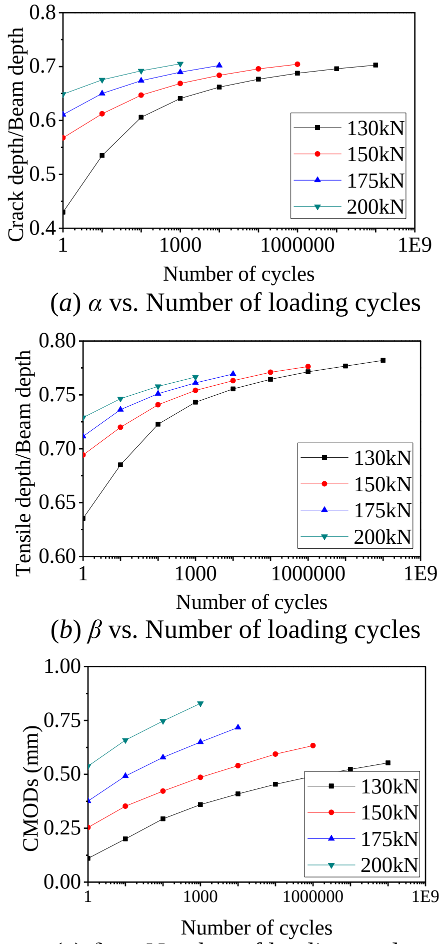


Fig. 4 Fatigue life from different approaches



(*a*) α vs. Number of loading cycles

(*b*) β vs. Number of loading cycles

(*c*) δ vs. Number of loading cycles

Fig. 3 Cracking state parameters vs. number of cycles

for Cold Region (CERI). Four load levels, i.e. 130kN, 150kN, 175kN and 200 kN, are selected for fatigue analysis. Based on the proposed method, the evolutions of cracking state parameters can be determined as shown in Fig. 3. With these results, fatigue life of the RC slab can be determined for different loading levels according to the failure criterion introduced in **2.4** as well. Moreover, the fatigue life can also be calculated following some empirical life prediction equations derived by different research groups, such as Matsui and Abe research teams, and institutions, such as JSCE and PWRI. Since these empirical equations were obtained through statistically fitting experimental data, each empirical equation represents a set of experimental results of RC slabs. Thus, these equations implicitly reflect the internal mechanisms and can be employed in life prediction of similar problems including the employed case in this study. All the S-N diagrams from the proposed method and the empirical equations and experimental fatigue life are plotted on a double-logarithmic scale as shown in Fig. 4. It is found that the theoretical S-N relation agrees well with the fatigue life from experiment and is almost the average of the four reported equations derived statistically, which verify the reliability of the proposed method.

4. CONCLUSIONS

A theoretical fatigue life prediction method has been proposed for RC bridge slabs which fail in a punching shear mode under cyclic moving loads. The method was established focusing on the propagation of punching shear cracks in a critical RC beam simplified from an RC slab. Concrete bridging degradation and bond slip degradation were considered as the source of crack propagation. From this method, fatigue life of RC bridge slabs were predicted for several loading levels. Comparisons between method predictions to results from experiment and some existing empirical life prediction equations indicated a good agreement which confirmed the applicability and reliability of the proposed method.

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