Comparisons of smeared crack models for RC bridge pier under cyclic loading

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Abstract: This paper presents a study of two different smeared crack models for RC bridge piers under cyclic loading. An existing multi-smeared crack model and a new plastic-damage-contact model, named Craft, which were implemented in the FE program LUSAS, are used in this investigation. At first the two models are verified through comparisons with experimental results for various cases of RC structures under monotonic loading. Then the models are used to predict the behaviour of a RC bridge pier under cyclic loading. Some comments are also made to the use of these models subject to earthquake-like cyclic loading.
Keywords: *smeared crack model, reinforced concrete, monotonic, cyclic loading, RC bridge pier.*

1. INTRODUCTION

This paper focuses on the performance of two plasticity-based smeared crack models, namely Multi-crack model [1] and Craft model [2]. Both of which were implemented into the commercial FE program LUSAS [3], for the analysis of RC in general and the modelling of bridge piers under cyclic loading in particular. In the following sections, the theoretical background of the models is first briefly described and then they are verified by analysing various cases of concrete and RC structures under monotonic loading. The models are then used for the analysis of RC bridge piers under cyclic loading. Emphasis is particularly placed on the evaluation of the models' capability to capture the cyclic behaviour before going to the next stage of the research programme, i.e. analysing the behaviour of RC bridge piers under artificially generated earthquakes.

2. NON-LINEAR FE SMEARED CRACK MODELS

2.1 Multi-crack model [1]

This model is based on plasticity approach to include the compressive behaviour of concrete and fracture approach to simulate directional cracking on defined planes. The unloading behaviour is essentially linear elastic though a reduced Young's modulus is used in the tensile unloading.

2.1.1 Concrete plasticity model

The two-dimensional plasticity model used to simulate the non-linear compressive behaviour of concrete is the one suggested by Jefferson [4].

2.1.2 Concrete fracture model

An empirical exponential softening curve is assumed and, for direct tension loading in one direction, the normal stress-strain relationship is shown in [3]. The model is based on a non-orthotropic law [5] which has a maximum tensile stress criterion for initial crack formation and subsequently the concrete is treated as non-orthotropic with the material strain softening in the direction normal to the crack. The yield function, which is applied to each crack direction, depends upon the local stress $s=(s_r\ s_s\ s_t)^T$, equivalent fracture stress f_s, and the friction factor μ, as follows:

$$F(s, f_s, \mu) = \frac{s_r}{2}\left[1+\left(\frac{\mu}{r}\right)^2\right] + \frac{1}{2r}\sqrt{(r^2-\mu^2)s_r^2 + 4r^2(s_s^2+s_t^2)} - f_s \le 0 \tag{1}$$

2.2 Craft concrete model

This new model, also suggested by Jefferson [2] uses modern plasticity, damage and contact theories and yet retains certain useful features of the Multi-crack model.

The damage, or contact, matrix is generated from planes of degradation, each of which is formed when a damage criterion is satisfied. The model employs a new crack plane model, which simulates both normal and shear degradation as well as crack closure effects. The model is also able to simulate the loss of tensile strength with compressive crushing and inelastic behaviour of concrete during the progress of tensile unloading.

3. VALIDATION OF THE MODELS UNDER MONOTONIC LOADING

3.1 Example 1: The first example is the analysis of an unreinforced concrete rectangular beam experiment conducted by Carpinteri [6]. The simply supported beam is loaded with a monotonically increasing load at the mid-span until the beam fails. The length between the two supports is 600mm and the rectangular cross-section is 100mm in height and 150mm in width. The concrete material properties used in the analysis are given in Table 1. In the FE model, the concrete is modelled using 2D 8-noded quadrilateral elements. The results of two different meshes: 56- and 224-element meshes are presented. The comparison in Fig. 1 shows that the results of Multi-crack and Craft models are in good agreement with the experimental result and also, analytical result [7]. It should be noted that fracture energy has been adjusted manually for Multi-crack model so that its behaviour is mesh independent [8]. As for Craft model, the adjustment has been done automatically.

3.2 Example 2: The second example is the analysis of a rectangular reinforced concrete beam (Beam 0A1) tested by Bresler and Scordelis [9]. The testing arrangement and the reinforcement are shown in Fig. 2. The concrete is simulated with 2D eight-noded quadrilateral elements with 9 Gauss points, and the reinforcement with three nodded bar elements. The concrete material properties used in the analysis are given in Table 2. The reinforcement properties are E = 205kN/mm^2, f_y = 553 N/mm^2. The steel is modelled as a one dimensional elasto-plastic material with a bi-linear stress-strain curve and a constant hardening modulus H = 15kN/mm^2. The numerical, experimental and analytical responses [7] are compared in Fig. 3.

4. MODELLING OF RC BRIDGE PIER UNDER CYCLIC LOADING

This is a model of a RC bridge pier which was tested under pseudo-dynamic condition during the PREC8 project [10]. The pier model has a solid double-T cross section and 0.90m in height. The pier is fixed at its foundation and is loaded at the top by a cyclic dynamic incremental control. A constant axial load of 150kN is applied at the top to model the transferred load from the superstructure. The FE mesh is given in Figure 4. The concrete is modelled with 2D 8-noded quadrilateral elements and the reinforcement is modelled with 3-noded bar elements. The concrete material properties are: E = 32kN/mm^2, f_c = 53.60 N/mm^2, f_t = 4.2 N/mm^2, ε_c = 0.004, and ε_0 = 0.0032. The reinforcement properties are E = 210kN/mm^2, f_y = 636 N/mm^2, and the hardening modulus H = 15kN/mm^2. Steel reinforcements include 6#6 bars for each layer of the pier (bold lines in Fig. 4). For simplicity, only longitudinal steel reinforcements are presented in FE analysis and it is assumed that there is full bond between the concrete and steel.

The numerical hysteretic response obtained from Multi-crack and Craft models are presented in Figs. 5 and 6, respectively, in which the experimental response is also given for comparisons.
It can be seen from Fig. 5 that, the latest Multi-crack model is, in general, not capable to capture the cyclic behaviour of the structure. The stiffness at unloading and the stress at zero strain during reloading and the values of peak load are too high. This is because, in the model, the unloading behaviour in concrete is assumed to be linear elastic with the initial modulus, and also it does not include the crushing effects of the compressive concrete.
In the contrary, the result of Craft model in Fig. 6 shows that the numerical hysteresis is generally in good agreement with the experimental one. The model can simulate the stiffness degradation of the pier in unloading and reloading behaviour very well. Also, as the model

includes the contacting effects in the concrete constitutive formulae [2], the pinching effect is well captured as seen in Fig. 6. However, the predicted peak loads at each cycle and stiffness at unloading are still slightly too high. This difference may be due to the slip between concrete and steel reinforcement. It should be mentioned that, at this stage, the complete result of numerical analysis has not been obtained yet because of the non-convergent problem.

5. CONCLUDING REMARKS

Regarding to cyclic loading, the Multi-crack model should be used with care if it is used for analysis of structures under cyclic loading as the damping and unloading stiffness have been overestimated. The result of the plastic-damage-contact model, Craft, is generally in good agreement with experimental results of the RC bridge pier under cyclic loading. It is because the model takes into account most of non-linear effects of concrete and reinforced concrete under cyclic loading. However, as the yield load at each cycle is slightly too high compared with experiment, slight modifications to the material properties will be checked and also, the consideration of bond slip between concrete and steel reinforcement may be necessary. Based on these investigations, Craft model is suggested to use for further analyses of RC bridge piers under cyclic and earthquake loading.

Table 1 Concrete properties for FE and analytical examples

Example	E_c (N/mm^2)	ν	f_c (N/mm^2)	f_t (N/mm^2)	ε_c	ε_0	G_f (N/mm)
1	34300	0.2	75.7	5.3	0.0022	-	0.09
2	25000	0.2	22.6	2.5	0.0018	0.0032	-

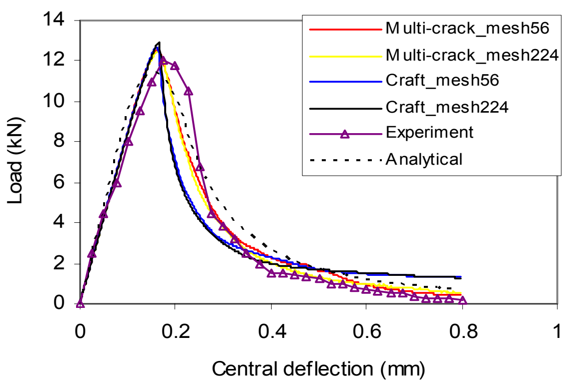

Figure 1. Load-central deflection - example 1

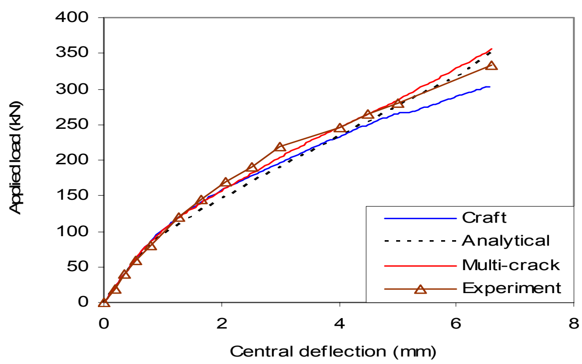

Figure 3. Load-central deflection - example 2

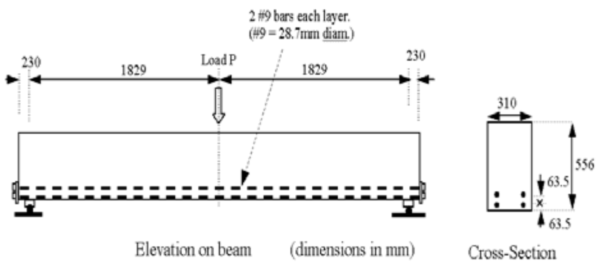

Figure 2. Experimental arrangement

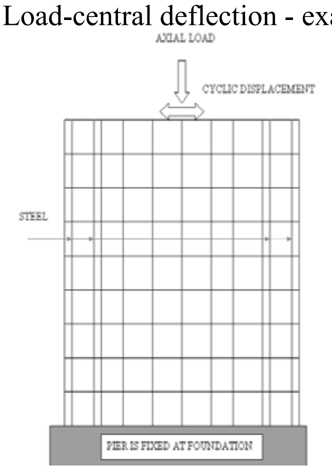

Figure 4. Finite element mesh of RC pier

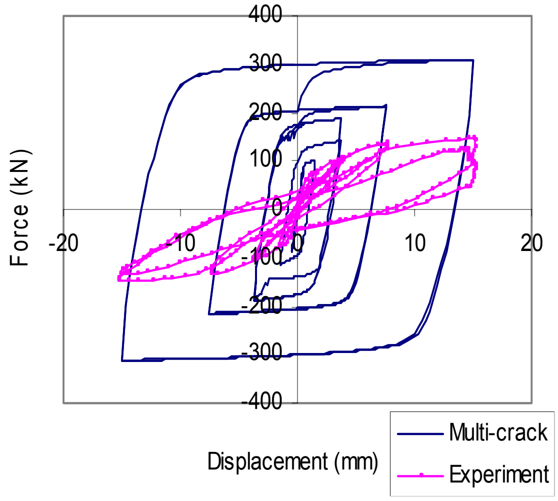

Figure 5. Finite element result, multi-crack model

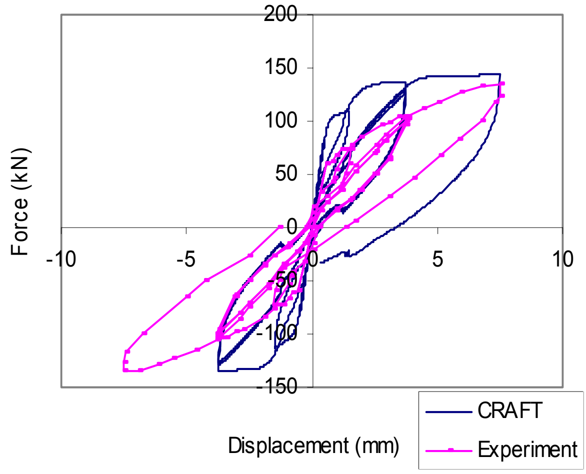

Figure 6. Finite element result, Craft model

6. FURTHER WORK

Craft model will be used to analysis RC bridge piers under artificially generated earthquakes which were generated from the EC8 elastic response spectra. This is part of the first author's research project at the University of Birmingham, namely "Modelling of RC bridge piers under randomly generated artificial earthquakes"

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