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Discrete element model for evaluating impact and impulsive response of reinforced concrete plates and shells

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ABSTRACT:The application of a discrte element representation of solids to the analysis of reinforced concrete plates and shells is discussed. Yielding of steel as well as fracture of concrete are duly accounted for by means of constitutive criterio that quantifies coupling between both effects. Comparison with experimental results show excellent correlation.

1 INTRODUCTION

The determination of the response up to the load carrying capacity of reinforced concrete shells subjected to impact and impulsive loads has been accomplished in recent years by numerous authors, by using finite element, finite differences or other formulations. However, the evaluation of the behavior beyond the structure carrying capacity, or after the peak load is reached, has led to less satisfactory predictions. In fact, the authors are not aware of any solution that closely matches the residual deformations or the vibration frecuencies in the damaged state. Preliminary studies in connection with fracture of concrete with this objective in mind were performed at the LDEC/CPGEC by Rocha (1989), and Riera (1989). The mechanical model is based on a discrete representation of an orthotropic solid based on previous results of Nayfeh and Hefzy (1978) and applied to the analysis of elastoplastic shell structures in a companion paper by Iturrioz and Riera (1995).

The same model was applied by Rocha, Riera & Krutzik (1991) to analize both a beam and a plate problem under impulsive loads, representing the behavior of the concrete elements by means of a bilinear force-displacement relationship inspired in Hilleborg's model (1978). Steel bars were assumed to be elastoplastic. Much larger fracture energy than measured in plain concrete specimens had to be assumed for the concrete elements in order to reproduce the experimental results. This fact has been reported in the technical literature, indicating that straight superposition of steel and concrete contributions, using elements of size larger than the size of the coarse aggregate is not feasible. Several modifications were later introduced, which led to a significant improvement in the prediction of the post-rupture response, and are described in this paper. The most important new features of the model are the following:

(a) Steel rebars are modelled considering the effect of the surrounding concrete. Thus, constitutive criteria for this composite steel-concrete element (STCR) are proposed.

(b) The fracture energy of concrete elements close to rebars is enhanced, in order to account for the fact that more than one crack will develop within the element due to the influence of the reinforcement.

2 FRACTURE IN REINFORCED CONCRETE STRUCTURES

Physically, the assumptions introduced by Rocha, Riera & Krutzik (1991) would correspond to steel rebars without bond, linked to the surrounding concrete at equally spaced nodal points. The results obtained by means of this simplification were considered unsatisfactory, principally bacause it required to artificially increase the critical fracture energy of concrete to values much higher than those observed in unreinforced specimens. The model proposed by Gupta & Maestrini (1990) was evaluated next, introducing in this manner the notion of a composite steel-concrete uniaxial element, that may be subjected to any stress-strain path. It was found however that a steel rebar alters the concrete properties is a volume around the bar, and in all directions. Then, a so called ductilization function f_{duc} was introduced, for every uniaxial concrete element in the model. As indicated in figure (1) , this function modifies the constitutive criteria, increasing the available fracture energy in the element. The largest value that f_{duc} may take, denoted ξ, lies, according to Linde (1993) in the range between 10 and 20. The value of f_{duc} for any given concrete element depends on its orientation and distance to the surrounding steel reinforcement, α_r and L_r respectively. A steel reinforcing bar thus alters the properties around it up to distances of the order of 3 L_c. This effect is considered independent of both the bar diameter and its surface configuration, factors that, if necessary, may be incorporated at a later stage.

Experimental results for a reinforced concrete beam subjected to impulsive loading due to Brandes (1981) were used for calibrate the above criterium.The layout of this beam and its mechanical properties, are shown in figure (2). Figure (3) presents the results of parametric studies over ξ and L_r . The values adopted were $\xi = 17$ and $L_r/L_c = 2$.

Once the peak load is reached, it was observed that to reproduce the structural response it must be admitted that the unloading branch of the STCR element must have a smaller slope than the loading branch, as shown in Fig (4). This can be explained by the fact that, after concrete cracking and yielding of the steel, some strain energy remains stored in the surrounding concrete, which is released upon unloading. Fig (5) presents a comparison of the experimental results for the Brandes beam (1980) with the numerical predictions before and after introducing the modification described above. It is clear that the effect is important, and in addition may allow the consideration of bond failure in reinforced concrete structures under damaging dynamics excitation.

3 IMPACT EXCITATION OF PLATES AND SHELLS

As shown by Iturrioz and Riera,(1995) and Riera and Iturrioz (1995), the procedure can be also applied for the analyses of elastoplastic plates and shells, with prediction capabilities similar to F. E. solutions , even in large deformation problems. Herein the model, incorporating the constitutive criteria described in section 2, is employed in the analysis of the slab tested at Meppen under projectile impact loading, (see Krutzik & Vinkier 1983). The slab dimensions, reinforcing and mechanical properties are given in a previous paper by Rocha, Riera and Krutzik (1991). A view of the model employed herein is shown in Fig. (6). Fig. (7) presents theoretical and experimentally determined displacements at point w9 and w10. Fig.(8) shows the final crack distribution on the lower face of the plate, together with the theoretical prediction for a quarter plate, in wich missing bars indicate fully craked concrete. It must be pointed out that the model considers the fracture energy as a random function of the spatial coordinates, which causes the loss of symmetry of the theoretical pattern in relation to the main diagonal. It is considered that this effect has only a marginal influence in the problem under study, which allowed the analysis of only one quarter of the plate.

4 CONCLUSIONS

A numerical procedure to determine the impact response of reinforced concrete structures is shown to yield improved predictions of the response of the damaged structure. New constitutive criteria to account for fracture energy dissipation as well as residual elastic energy recovery during unloading are introduced in the formulation.

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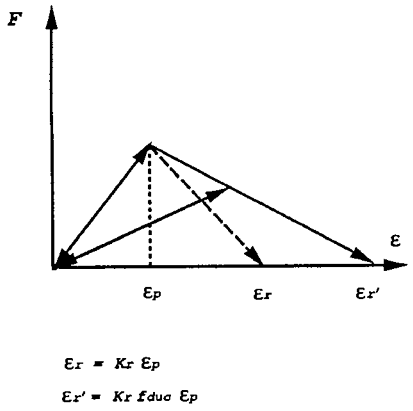
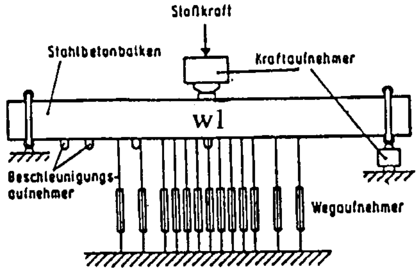
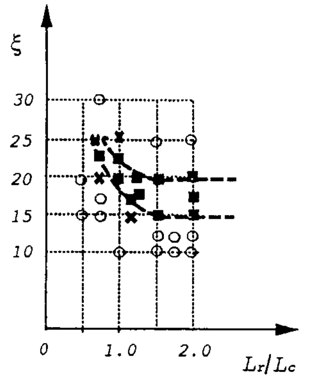


Figure 1: Constitutive law of concrete bars affected by the reinforcement.



Ec = 3000MPa
$\nu = 0.2$.
Es = 210000MPa
fy = 495MPa

Figure 2: Layout of Brandes beam (1981) and the principal geometric and mechanical properties.



■ - All simulations presented satisfactory correlation with experimental results.

✖- Some simulations led to a satisfactory correlation, others presented poor correlation.

○- All Simulations led to poor predictions of the experimental response.

Figure 3: Parametric study of the variables ξ and L_r/L_c.

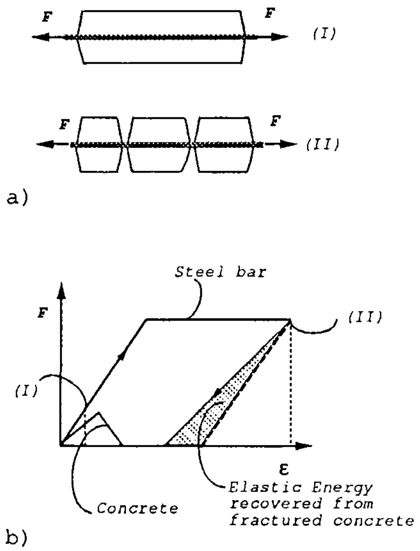


Figure 4: a)Reinforced concrete specimen before and after frature. b)The constitutive law of steel and concrete adopted in the DEM model.

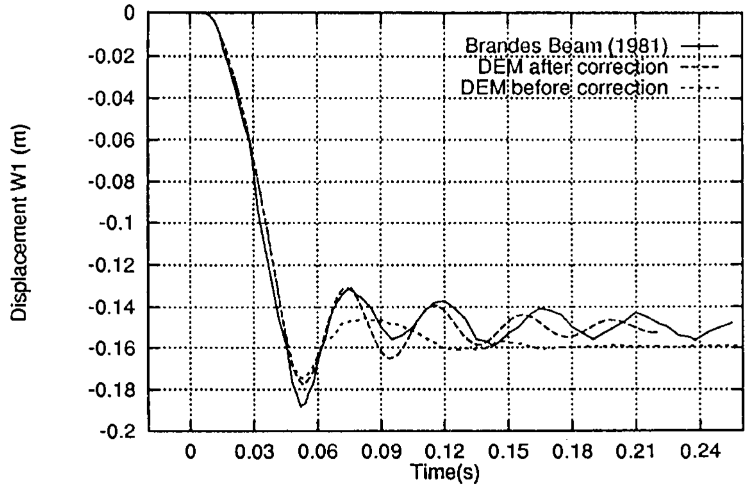


Figure 5: Comparison of experimental and numericals response: midspan displacement vs. time for Brandes beam (1981).

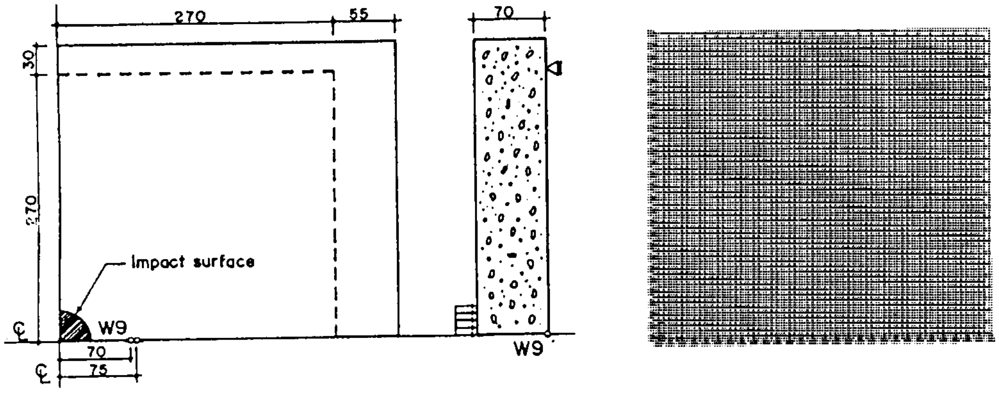


Figure 6: Layout and Properties of the MEPPEN plate (Krutzik and Vinkier 1983), and the DEM model of one quarter plate.

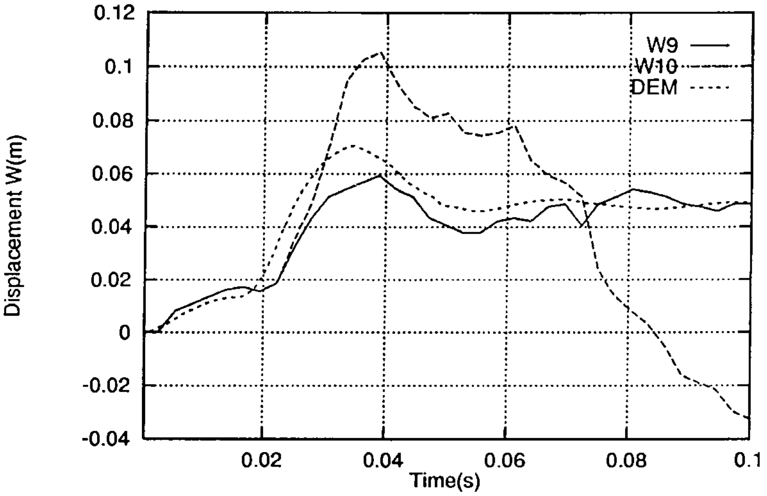


Figure 7: Comparison of experimental and numerical responses: normal displacements vs. time of the MEPPEN plate (Krutzik and Vinkier 1983).

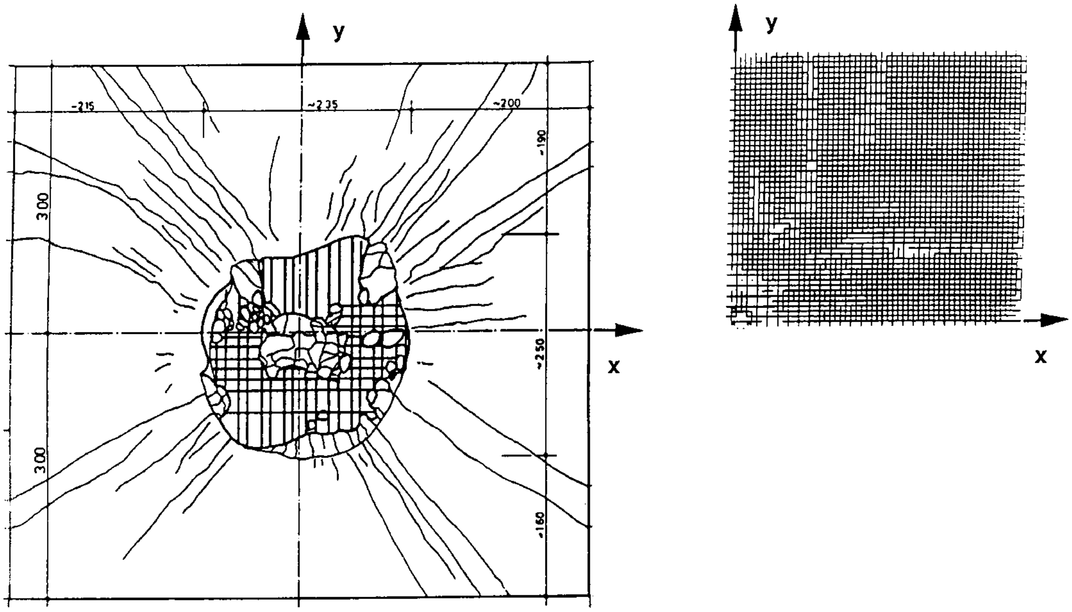


Figure 8: Experimental and theoretical crack patterns in Meppen test.