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Failure and Post-Failure Analysis for Extreme Loads

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Abstract
Strain rates vary in a big range by extreme loads of concrete structures. The concrete behaviour is influenced by the strain rate. In the presented work three examples of extreme loads on concrete were shown. Containment structures are quasi-statically loaded by an accident with high internal pressures and temperatures over 200 degree Celsius. For the simulation of the results by earthquake is a dynamic constitutive law has to be used. The third example is concrete under the influence of impact and blasting. The effects of strain rate and Hugonit are to consider.

1 Introduction

Concrete acts different if it is loaded due to extreme events. We present three examples of such loads and their simulations. The differences between the examples are the strain rates shown in figure 1.

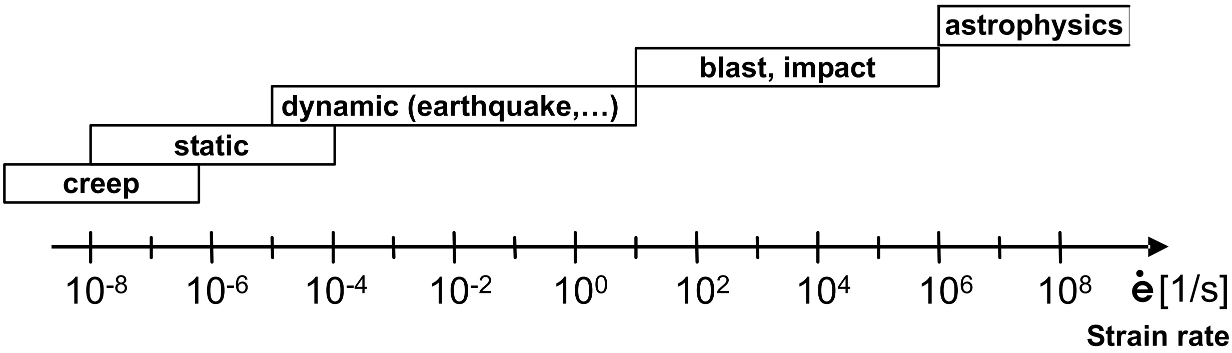

Figure 1: Strain rates

2 Containment structures

One example for concrete structures under extreme loads are concrete containments for power plants. During severe accidents high internal pressures and temperatures over 200 degree Celsius can occure and last for several hours. The loads are quasi-static with quite low strain rates but long application of the loads. The non-linear temperature profiles with high internal temperatures and almost constant temperatures on the outside of the thick structures leads to high thermal strains.

To improve the knowledge about the behaviour of these structures under severe accident conditions experiments on representative wall segments were performed by the Institut für Massivbau und Baustofftechnologie [1]. For the numerical simulation of these experiments the Finite Element Program ADINA was used and a structural model was developed.

The concrete parts of the specimen were modelled with 4-node solid elements with a concrete material model developed at the Institut für Massivbau und Baustofftechnologie. In the implemented material model, a macroscopic damage evolution model is used with isotropic damage in compression. In the case of tension a combination of the fictitious crack model and the crack band model is used.

A reduction of the concrete strength at higher temperatures and a temperature dependent Youngs modulus can be taken into account.

Since the development of cut-through cracks through the whole depth of the structure and the width of these cracks is of high importance for the safety of containment structures and this is mainly influenced by the reinforcement layout and the bond mechanism between the reinforcement and the concrete the wall segments were modelled with discrete reinforcement.

For the modelling of the reinforcement, 2-node truss elements were used. These elements were connected to the solid elements with 4-node bond elements with an embedded bond model.

3 Seismic Performance of Bridge Piers

The failure of numerous large bridges after recent earthquakes especially after the 1995 Kobe (Japan) earthquake caused a severe impact on infrastructure. Mainly older bridges built according to an inadequate elastic design philosophy revealed various forms of failure [3]. However even bridges built according to new standards obviously have deficiencies like the Hanshin Expressway in Kobe that collapsed due to pier-failure after the 1995 earthquake.

Actual safety concepts demand high ductility in the structure that means the structure shall largely deform without loss of resistance. A commonly accepted criteria at bridges is that the inelastic deformations shall not occure in the superstructure [2]. Thus nonlinear behaviour is restricted to seismic bridge bearings or piers. In the actual study the seismic performance of R/C piers is investigated and optimized. The pier has to be able to perform stable load-deflection hysteresis loops with sufficient energy dissipation in order to decrease earthquake forces not only in the pier itself but also in adjacent structural parts. Furthermore it is essential that the residual plastic deformations after an earthquake remain acceptable.

An efficient numerical model had to be developed in order to investigate the numerous factors influencing the overall seismic pier-performance. The numerical model is based on the fibre beam theory and is implemented in the general purpose Finite Element Program ABAQUS. It considers the nonlinear behaviour of concrete, steel, and bond for cyclic loading. The biaxial bending due to earthquake excitation of axially loaded slender piers can be simulated. Distinct from previous fibre formulations the reinforcement is superposed by extra truss-elements and connected via bond elements to the nodes of the fibre-elements ([5], [4]). In this way it is possible to realistically consider successive opening of cracks and deterioration not only of concrete and steel but also of bond.

The numerical model was compared to various experimental results from literature [2] and shows good agreement for monotonic as well as for cyclic loading.

A parametric study using nonlinear time-history analysis is in progress in order to investigate the influence of longitudinal steel ratio, concrete strength, steel ductility and ratio of axial load to ultimate load on the seismic performance of piers. Furthermore an actually discussed positive effect of a vertical prestressing of piers will be investigated using the same numerical model. First results show that due to cracking of concrete the ductility of steel is a leading factor on the pier-performance. On the other hand prestressing can limit the crack opening and therefore limit the residual deformations of the pier due to an earthquake.

4 Blasting and impact

Blasting and impact are further examples for concrete under extreme loads. The numerical problems of both are high pressure (until 20.000 MPa) and high velocity with high strain rate. The strain rates are approximately 10^2 to a 10^6 per second. Shock waves are developed in the concrete.

Discrete cracks are useful to model concrete under high strain rates. So a simple constitutive law is usable and it is also possible to use the discrete cracks to calculate the fragmentation after the blasting. Another possibility is to model cracks on element edges. This needs a remeshing by growth of the crack. Elements with discontinuities inside (like the extended finite element method (XFEM)) do not need any adaptation by crack growth.

4.1 Element-free Galerkin method

Belytschko [7] has shown the element-free Galerkin method (EFG). Only nodes are used and no elements. The idea of EFG is to modify the shape functions from the finite elements with shape functions build by a Moving-Least-Square interpolation. The shape function shows the influence of one node on another and depends on their distance. In EFG the adaptation is very simple and therefore cracks are also possible to simulate with EFG by cutting the shape-function at the crack.

EFG is used with explicit time integration for the simulations of concrete under the extreme loads of blasting and impact. Curbach [8] showed that the maximum velocity of the crack growth is 500 m/sec. In contrast the velocity of the shock wave is 4000 m/sec. So the growth of the crack is to restrict to a value of 500 m/sec.

In addition to the discrete cracks the constitutive law includes the following parts to model concrete under this high strain rates.

4.2 Strain rate effect

In experimental tests the tensile strength is increasing with the growing strain rate. Values up to a tenfold increase were measured. The reason for this is the homogenization of the concrete under this high strain rate and the delay of the development of the micro cracks.

4.3 Hugoniot - Shock waves

The hydrostatic strain-pressure relation is extremely nonlinear. The gradient in this relation is due to the hydrostatic stiffness. The corresponding waves to a constant stiffness are elastic. With increasing stresses the stiffness is decreasing because of the destruction of the micro pores. The corresponding waves are plastic and the velocity of the corresponding waves is slower. If the micro pores are damaged the stiffness is increasing again. The corresponding waves with this pressure are faster then all the other waves. These waves overtake the other waves and build up a shock front. The relation between the hydrostatic strain and the pressure has been measured at the Institut für Massivbau und Baustofftechnologie [9] and is used in the constitutive law.

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