# Damage prediction in a concrete bar due to a compression and tension pulse

## - A comparison of the K&C, the CSCM and the RHT material models in LS-DYNA

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## Abstract

Advanced Finite Element codes provide the possibility to simulate high rate loading on concrete targets as ballistic impact and explosions. Although damage to RC structures due to these loadings can be simulated and detailed results can be obtained the predictions are still far from perfect. It is well known that the results strongly depend on the numerical material model. In a collaboration project of AFA, IST, Delft University of Technology and TNO damage prediction in concrete panels due to close in explosions and the residual bearing capacity are studied.

The hydrodynamic finite element computer code (Hydrocode) LS-DYNA was chosen as the computational tool to pursue this research. The first step was the comparison and analysis of the three most advanced concrete models implemented in LS-DYNA: Karagozian & Case Concrete model (KCC), Continuous Surface Cap Model (CSCM) and Riedel, Hiermaier and Thoma (RHT) model. The models were tested under a wide range of configurations in order to evaluate their response under different stress states and loading rates. In this paper our attentions are focus on the damage development in compression and tension. Bar tests were modelled in order to explore the material model's dynamic response in a more controlled way.

## Introduction

High-velocity impacts and close-in (contact) detonation produce extremely high load amplitudes (pressures in the order of GPa), high loading rates and high temperatures within microseconds. The consequence is a complex process of interfering stress waves combined with the damaging and failure of the concrete material. The initial response is dominated by the response to the induced stress waves. The structural response only becomes relevant after several wave reflections and the energy is transferred to the target over a region several times its thickness [1]. With the research

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aim to predict the damage and residual bearing capacity of RC slabs subjected to close in detonation, the first focus is on the concrete response to (combined) compressive and tensile stress waves.

Considering the example of a concrete slab subjected to a contact detonation, the material is subjected to multiple states of stress which leads to different rupture modes: cratering, cratering plus scabbing or perforation [2]. Figure 1 shows the failure mechanisms plausible to occur on a slab under a contact detonation of median intensity.

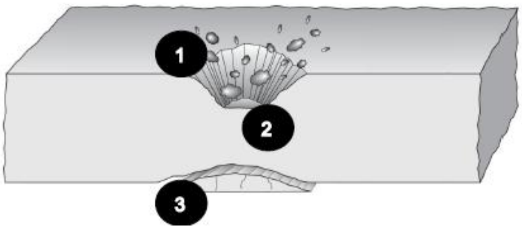

**Figure 1 Damaged concrete slab after a contact detonation (with moderate intensity)**

Immediately after the detonation a state of very strong hydrostatic compression is observed (in the tens of GPa range), high strain rates ($10^5$ to $10^6$ $s^{-1}$) and shock heating leading to an irreversible compaction and crushing of the material leading to the crater formation (1). Due to the short pulse length and dissipation processes and geometrical expansion, the amplitude of the induced pressure pulse rapidly decays. At the free opposite surface the already damped shock wave reflects in a dispersive manner, leading to a tensile pulse with a one to two orders of magnitude lower loading rate than the compressive one ($10^3$ to $10^4$ $s^{-1}$) (Riedel and Forquin in [1]). Scabbing occurs (3) due to the material's low resistance to tension. When the cratering and the scabbing process interfere perforation occurs. In the transition zone (2) the concrete material is initially subjected to a compressive wave immediately followed by a tensile one. During this process the material is exposed to rapidly changing multiaxial stress conditions.

The development of numerical models capable to predict damage development and residual bearing capacity of concrete structures exposed to extreme dynamic loadings is a real challenge and currently at the edge of computational techniques, material models and even on the understanding of the physical behaviour of concrete under these loading conditions. With LS-DYNA as computational platform, the first step of our research was to study and evaluate the concrete material models available under the given dynamic loading conditions. From the LS-DYNA library we chose three material models suitable to simulate concrete's dynamic behaviour: Karagozian & Case Concrete model (KCC), Continuous Surface Cap Model (CSCM) and Riedel, Hiermaier and Thoma (RHT) model. In this report we focus on study and compare these models. First we performed a series of basic cell-test to complement our overview on the models constitutive laws. Then, different bar experiments were modelled in order to evaluate and compare the damage development. These one dimensional wave propagation problems are a controlled way to study the dynamic compressive and tensile behaviour of the material.

## Computational modelling of concrete under severe dynamic loading

Most material models available in hydrocodes are phenomenological models based in the classical continuum theories of plasticity, viscoplasticity (e.g. [7], [8]), damage mechanics [9], and different combinations of these (e.g. [4], [10], [11]). In these models the material strength ($\sigma$) is governed by more or less complex relations of strain ($\varepsilon$), strain rate ($\dot{\varepsilon}$), volume or density ($V$ or $\rho$), internal energy ($e$) and damage ($D$) – $\sigma = f(\varepsilon, \dot{\varepsilon}, \rho, e, D\ )$. Usually the stressis split into the volumetric and deviatoric part according:

$$\sigma_{ij} = {}^{1}\!/_{3}\, \sigma_{ij}\delta_{ij} + S_{ij}$$

with $\sigma_{ij}$ as the Cauchy stresses, $S_{ij}$ the deviatoric stresses and $\delta_{ij}$ the Kronecker Delta function. The volumetric deformation, associated with the non-linear behaviour under hydrostatic pressure ($p$), is described by an Equation of State (EoS) (Figure 2 left). This relation is usually derived from flyer plate impact tests and describe the materials volumetric behaviour in a shock loading situation. Is should be notice that this is an adiabatic description.

The deviatoric part, associated with triaxial behaviour, is usually modelled by a classical continuum theory (plasticity, viscoplasticity, damage mechanics, etc.) and represented by the strength criteria. The yield surfaces or strength envelopes (Figure 2 right) (elastic, maximum strength and residual strength) represent the triaxial stress limit of a specific material behaviour described by the elastic and plastic theories. The non-linear behaviour of the material (softening) usually follows an energy based damage law.

Finally, the strength enhancement due to rate effects is usually included in the models through a Dynamic Increase Factor (DIF) or viscosity and a flow potential gradient that represents the direction of the plastic strain rate.

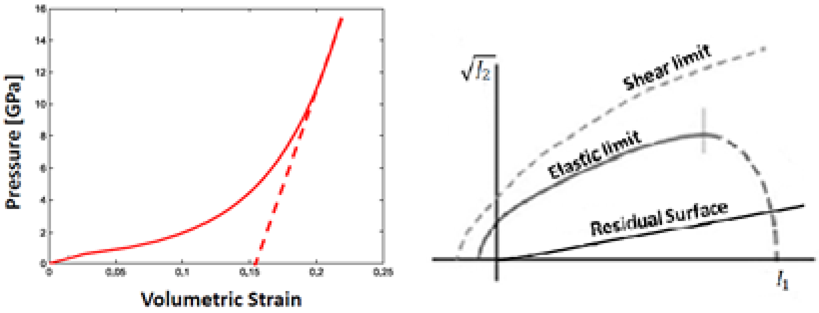

**Figure 2 Schematic representation of the EoS and the strength envelops (yield surface)**

## Comparative study of LS-DYNA concrete models

From the concrete constitutive models implemented LS-DYNA we selected the three most suitable material models for the modelling of a contact detonation: 1) Concrete Damage models release 3 (MAT072REL3) commonly known as the Karagozian and Case Concrete model (KCC) [4];

2) Continuous Cap Surface Concrete model (CSCM – MAT159) [5]; and the Riedel-Thoma-Hiermaier concrete model (RHT – MAT272) recently added to LS-DYNA's library [6]. After a theoretical overview of these models we conducted a series of tests with increasing complexity to promote a better familiarization and for better understanding of the material models and the software. We started with the study of their basic features by performing cell tests for uniaxial compression and tension, triaxial confinement and hydrostatic compression tests. We also studied other aspects as mesh dependency, the applied regularization techniques and the rate effects. The results are used in the response analyses of bars exposed to an axial pressure pulse load as described in the next section.

## ***Material models characterization***

The three models evaluates in this paper (KCC, CSCM and RHT) can be categorised as isotropic, plastic-damage and rate dependent models. The implementation schemes are similar and can be divided into: i) strength surface (Figure 3) and EoS formulation (Figure 4); ii) elastic and plastic updates (Figure 5); iii) damage accumulation (Figure 5); iv) rate effects and v) energy regularization (mesh size dependency).

All models consider the Hooke's law to describe elastic behaviour. The damage and plastic response of the material are related. The rate dependency is incorporated in the strength models by a DIF function or a visco-elastic relation used to modify the strength envelopes. The KCC and RHT[‡] use formulations based on CEB (1993) [12] and the CSCM models use a visco-plastic function. The CSCM and RHT models consider a CAP formulation to describe the compaction of the material. The damage formulation of the KCC model is particular because it describes pre-peak non linearity as well as the post-peak softening behaviour of the material and is defined in a scale 0 to 2 by a non-linear relation between the softening and damage law. In the other models damage is scaled in a more common way from 0 to 1. These damage laws are only described in the deviatoric space, therefore no compaction (hydrostatic) damage is considered. Several review of this material models can be found in the literature, however none exists considering the RHT concrete model version implemented in LS-DYNA (e.g. [13], [14], [15], [16], [17]).

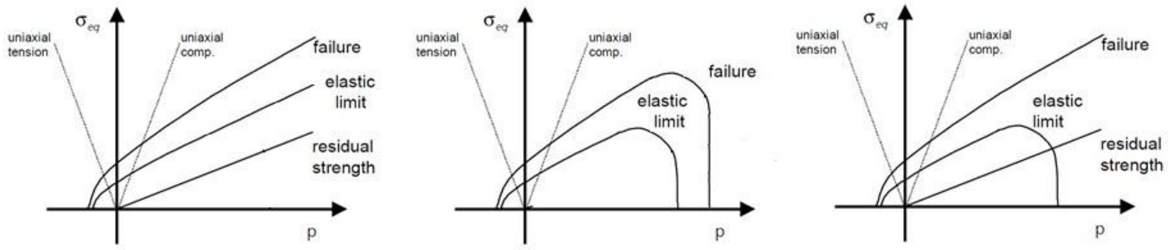

**Figure 3 Strength envelops scheme: KCC (left), CSCM (middle) and RHT (right)**

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[‡] By default the RHT parameters are not in agreement with the CEB formulation. The parameters EC and ET must be set to 30 $s^{-1}$ and 1 $s^{-1}$ respectively.

Figure 4 and Figure 5 show hydrostatic and uniaxial compressive and tensile response of the material. Considering the discrepancy between the EoS considered in the models and between these and the experimental information available [18] (see Figure 4), we proposed and analysed a modified version of the KCC model, the KCC2, where the EoS was updated by the Gebbeken's formulation [19]. As can be seen in Figure 5, by only changing the EoS, the material response for uniaxial compression and tension changes considerably. This is a consequence of the computation sequence in the models, where the EoS is used first to compute the pressure (or first stress invariant – $I_1$) and only then the deviatoric stresses ($S_{ij}$) are computed.

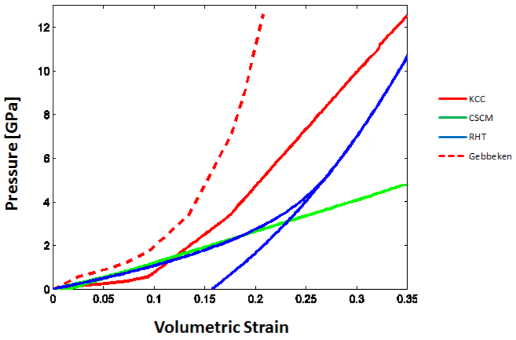

**Figure 4 EoS for the different models compared with Gebbeken's formulation [19]**

Figure 6 shows the results of the mesh sensitivity study. RHT considers the same stress-strain relation independently on the mesh size, therefore the energy absorption is directly related to the element size (note that the energy values exceed the scale in Figure 6 for the 50 and 100 mm mesh). KCC consider a crack band model (for tensile stresses) for regularization where the energy absorption is the same in element sizes between 25 and $250mm$ (see Figure 6 right). For smaller elements the fracture energy is reduced proportionally. In compression no regularization is applied. The CSCM model considers the same failure strain independently on the mesh size, but changes the softening law in order to achieve a constant fracture energy. Figure 7 shows the uniaxial responses at different loading rates. RHT and KCC exhibit a similar change in response because both use the same DIF function to change the strength limits (surfaces) and consequently the stress-strain response. In the CSCM model, the rate enhancement function only change the peak strength.

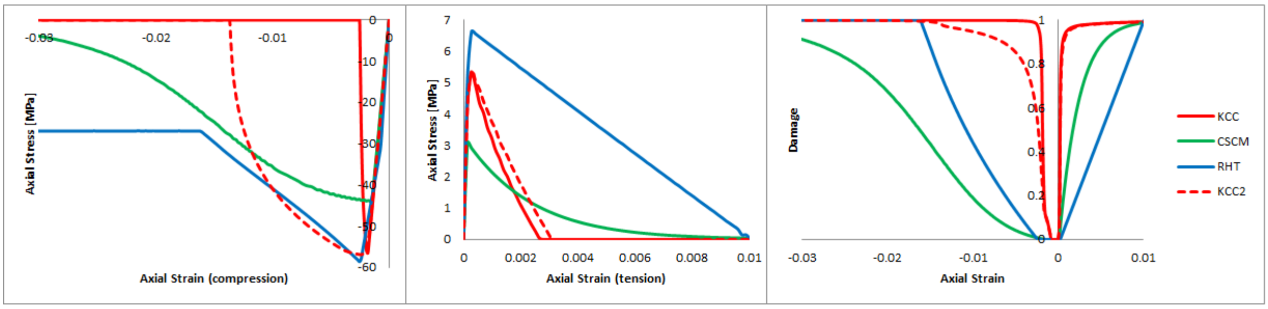

**Figure 5 Material's uniaxial behaviour. (left) Stress-Strain relation; (right) Damage (mesh= $10mm$ and loading rate = $1s^{-1}$)**

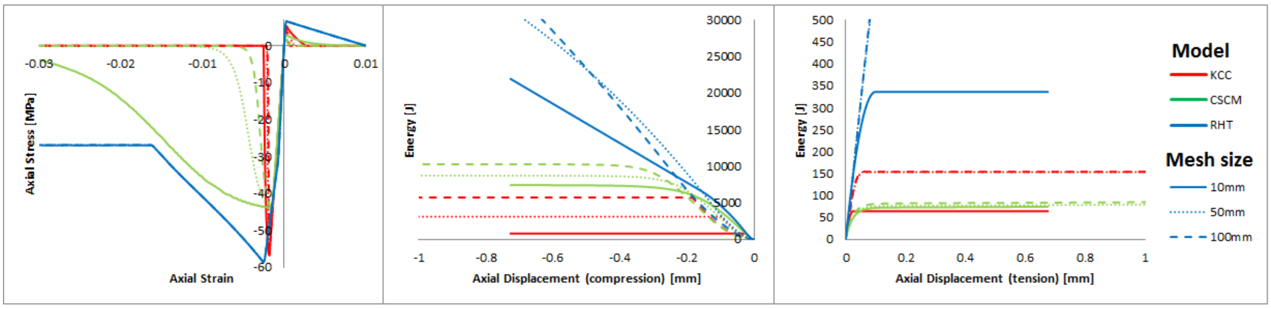

**Figure 6 Mesh sensitivity analysis. Stress-strain (left); energy absorption in compression (middle) and energy absorption in tension (right). Mesh sizes: $10mm$, $50mm$ and $100mm$**

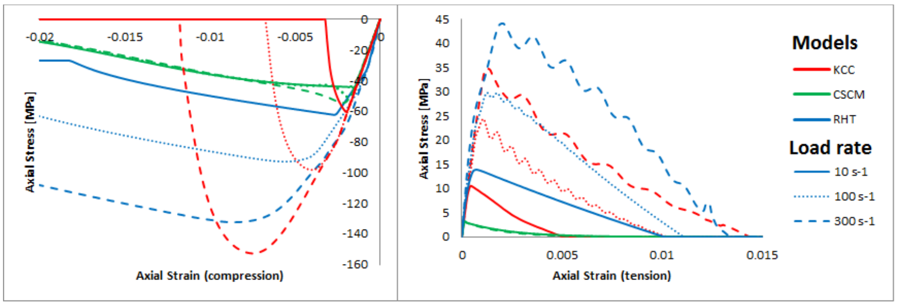

**Figure 7 Loading rate effect in compression (left) and tension (right). Loading rates: 10, 100 and $300s^{-1}$**

## *Wave propagation in a concrete bar – comparative study*

The Split Hopkinson (Kolsky) Bar (SHB) in its different configurations have been widely used to study the dynamic strength of materials. Considering their simplicity, this experiments are the perfect set up to continue our evaluation which allow us to study the wave propagation, wave interference combined with the material failure characteristics of a close-in explosion loading situation. Hence, a concrete bar, $250mm$ long and $74mm$ diameter subjected to a pulse load was modelled to study the material models dynamic response (see Figure 8). The loads were modelled as a variable pressure with different intensities ($P_{Max}$) and duration ($T$). Although different shapes of pressure pulses were tested, we opted to use sinusoidal ones to minimise dispersion (material and numerical) effects.

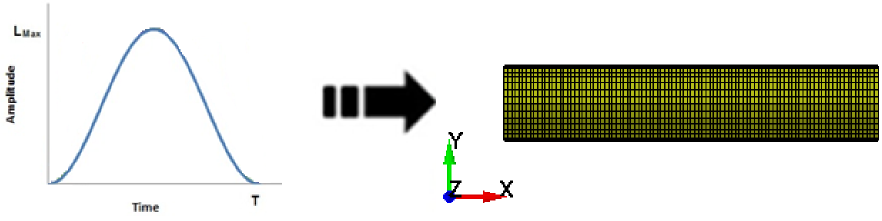

**Figure 8 Concrete bar model**

To study the tensile response of the models the pulse intensity was kept bellow the materials compressive strength to prevent compressive damage and the pulse length in the limits to guaranty tensile failure after reflection ($45\ \mu s < T < 180\ \mu s$). This configuration is consistent with the modified SHB, known as spalling test, used by several researchers to study the dynamic tensile properties of concrete (Weerheijm, Schuler, Forquin, in [1]). **Figure 9** and Figure 10 show relevant results for a pulse load with $T = 90\ \mu s$ and $P_{Max} = 40MPa$. **Figure 9** show the final damage for different mesh refinements. The damage results for each model are clearly different. This is due to the difference in damage definition and description. RHT and KCC consider a linear relation between damage and the softening law, while the KCC does not and also counts for pre-peak damage (see Figure 5 right). Another cause is the difference in stress-strain relations and the value of the failure strain. The CSCM and KCC models have a more brittle behaviour than RHT. The RHT "absorb" more energy and allow bigger tensile deformation before failure (see Figure 6 right).

Figure 10 shows the axial stress evolution in four points along the specimen core, the first point is at $25mm$ from the loading surface ($P1$) and the other three are at an interval of $25mm$ from the first section to damage ($P2$ to $P4$). Although the damage predictions are all different, comparing the transmitted waves after the damage (blue line Figure 10) in the KCC and RHT results they are similar. The CSCM model results (damage and displacement) reveal a high mesh size dependency justified by the constant fracture energy considered independently the mesh size (see Figure 6 right).

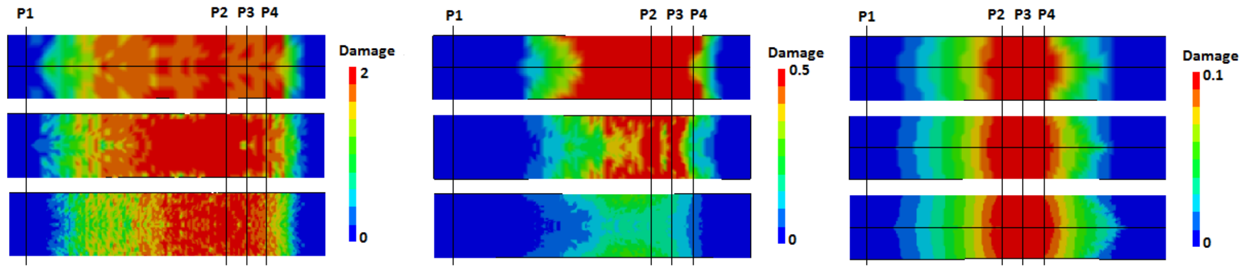

**Figure 9 Damage prediction at different mesh sizes: 5mm (top), 2.5mm(middle) and 1.25mm(bottom). Models: KCC(left) – scale: 0 to 2, CSCM(centre) – scale: 0 to 0.5 and RHT(right) – scale: 0 to 0.1**

Figure 11 and Figure 12 show the damage results and the axial stress evolution in several points of the bar along the specimen core, for a pulse load with $T = 45\ \mu s$ and $P_{Max} = 300MPa$. These results illustrate the dynamic compressive response of the models. As in the tensile case, the damage and deformation results of the models are all different (see Figure 11). The differences in the wave propagation histories are more evident now.

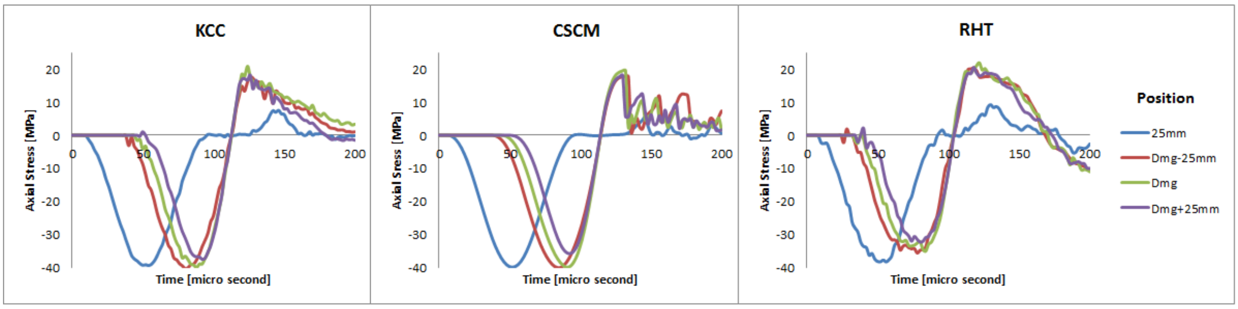

**Figure 10 Axial stress evolution at four point along the bar for low intensity pulse load: ($T = 90\mu s$ and $P_{Max} = 40MPa$). KCC (left); CSCM (middle) and RHT (right)**

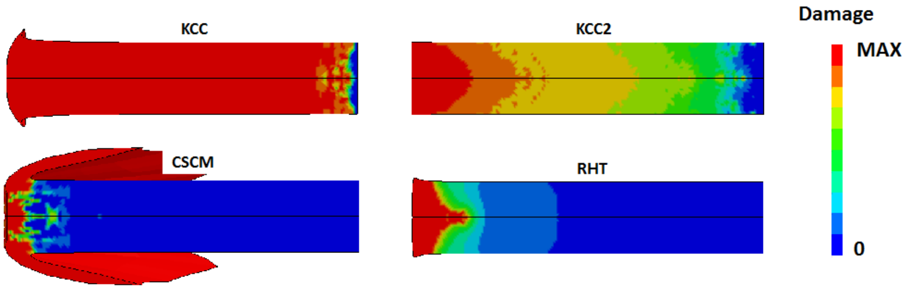

**Figure 11 Damage for intense pulse load: ($T = 45\mu s$ and$P_{Max} = 300MPa$)**

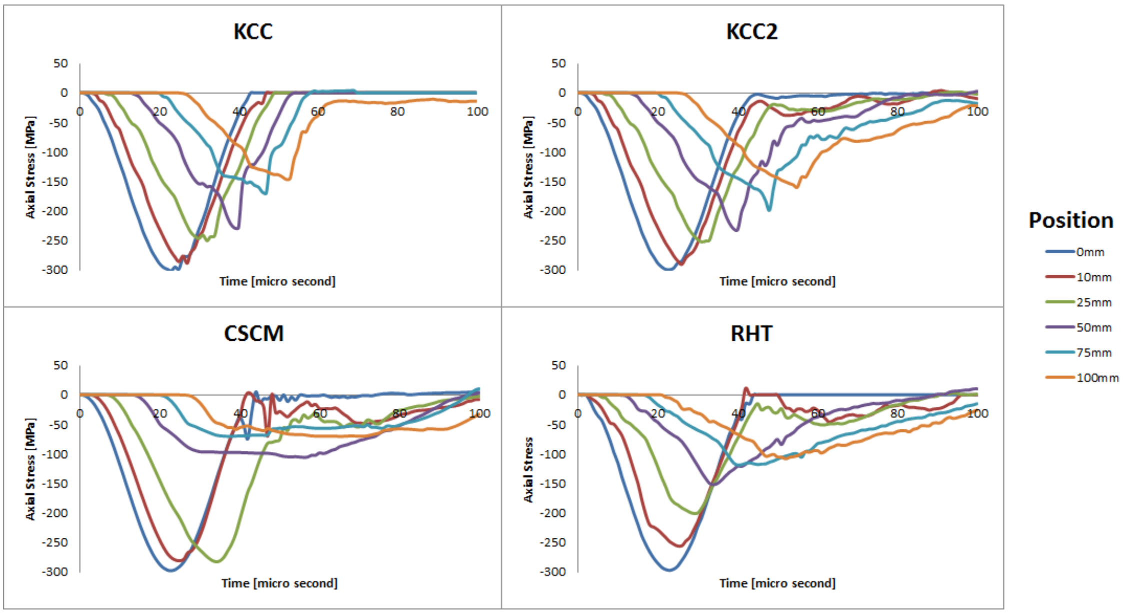

**Figure 12 Axial stress evolution at four point along the bar for intense pulse load:**
**($T = 45\mu s$ and $P_{Max} = 300MPa$)**

It is interesting to observe the difference in results for the two version of the KCC models. This is a consequence of the different stress-strain relation obtained by changing the EoS (see Figure 5). The response of the KCC2 is more ductile, the damage grows much slower and the descending branch of the transmitted pulse is much longer (see Figure 12). The RHT and CSCM models predict a very localized damage zone and the transmitted waves disperse rapidly (loading intensity and rate decreases). This is due to an higher energy absorption in the first portion of the bar. Hence, the failed material act as a “load filter” for the remainder of the bar, which properties are determined by the EOS, the strength envelopes and the damage definition in the material models.

## Conclusions

Modelling damage and residual bearing capacity under impact or close in explosions, requires reliable prediction of wave propagation. So it is of major importance to understand the wave interference combined with the material response at each point (time step) of a simulation. Consequently the applied material model, its parameterization, constitutive relations and residual properties are decisive for the final prediction. Hydrocodes have been successfully used in analysis of wave propagation in continuous media. The predictions of RC structures behaviour under impact and explosions have been achieved with this codes, but the results strongly depends on the applied material model and the available data to calibrate the models.

This paper presents results of a comparative study of three concrete models implemented in LS-DYNA: Karagozian & Case Concrete model (KCC), Continuous Surface Cap Model (CSCM) and Riedel, Hiermaier and Thoma (RHT) model. The simulation of elementary bar experiments are presented to illustrate and compare the dynamic compressive and tensile response predictions for these models.

It is shown that damage data are not suitable to compare different material models because the damage parameter is not uniquely defined. The damage and softening process strongly depends on (i) the applied damage function related to the deformation in the failure zone and (ii) the final failure deformation (failure strain, related to element size). It should be noted that only some experimental data on the deformation at complete failure is known for uniaxial compression and uniaxial tension loading and not for multiaxial loading conditions. This dependency is an assumption in the models.

It was also observed that the calibration of the model's EoS (and strength envelops) have a significant influence on the model response in the 1D-bar experiments. The zone of damaged material acts as a "load filter" for the remainder of the structure. The properties of the filter are determined by the EOS, the strength envelopes and the damage definition in the material models. All these different aspects of the models have to calibrated together consistently.

Based on the results obtained so far it is concluded that the CSCM model is not adequate to model RC response for extreme dynamic loadings like ballistic impact and close-in explosions. The KCC and RHT models provide promising results.

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