Limitations of smeared crack models for dynamic analysis of concrete

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Summary

Performance prediction of concrete structures under explosive loadings or impact is an essential part of the research that is being performed within TNO. One of the current research topics is the explosive safety of tunnel structures. In the context of this research we evaluate the capabilities and limitations of concrete material models in LS-DYNA. The evaluation focuses on the CSCM concrete model and in particular the damage and failure characteristics of the model under single and sequential compression and tensile loading.

Like many existing concrete models, the CSCM uses a smeared crack approach to model the reduction in strength of damaged concrete. It will be shown that the smeared crack approach has an intrinsic limit that places a restriction on the minimum size of an element. Furthermore, it is predicted that the built-in fracture energy regularization further aggravates the situation. The regularization algorithm tries to maintain a constant fracture energy. When elements have a size that is smaller than the limit size, the fracture energy of the total structure is increased which causes non-physical behavior. The predictions are confirmed by analyses on a tunnel structure as well as analyses on concrete cylinders under tension and compression.

In contrast to the established minimum width, high dynamic loads or very local loads such as explosions or impact require a very fine mesh that can accurately describe the stress state and the shockwaves that are induced during these events. Using a reference load of a BLEVE explosion, the desired element size is derived and it will be shown that the desired element size is far smaller than the lower limit of element size. The consequences of the conflicting restrictions on the element size by the material model and the dynamic loading are illustrated by the tunnel structure analysis.

To summarize, the following conclusions have been drawn:

- *A minimum element size was found for the CSCM model*
- *The smeared crack approach is the source of this limit*
- *The established minimum element size will most likely not be in correspondence with the desired mesh when analyzing high dynamic events*

Non local models may hold the key in overcoming the limits imposed by the smeared crack analyses. This will be a topic for future research.

1. Introduction

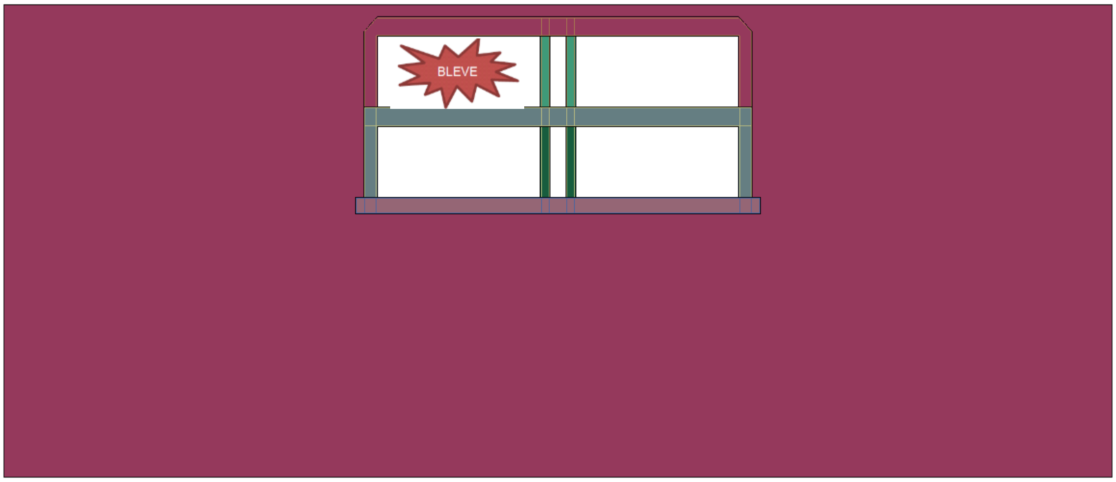
Performance prediction of concrete structures under explosive loadings or impact is an essential part of the research that is being performed within TNO. One of the current research topics is the explosive safety of tunnel structures.

During the course of this project it was discovered that the results for different mesh sizes were highly mesh dependent. This results incited further research into the background of treatment of cracks in the concrete models.

2. Mesh analysis for simulating a explosion in a tunnel

The initial project started with an analysis of a generic tunnel structure that is loaded with a BLEVE blast loading (Weerheijm, 2010). The tunnel structure contains 4 sections, consists of concrete walls, reinforced with steel rebars and surrounded with soil. The BLEVE loading (500 kPa, $t_{decrease}$=100ms) is applied in the upper left section.

Below is an impression of the 2D plane strain model and the location of the BLEVE blast loading.



In the analysis, the following material properties have been used:

Material	Model	Characteristics
Concrete	*MAT_CSCM	ρ=2170kg/m^3, F_c = 30MPa
Steel	*MAT_PLASTIC_KINEMATIC	ρ=7850kg/m^3, E=210GPa, υ=0.3
Soil	*MAT_ELASTIC	ρ=2000kg/m^3, E=100MPa, υ=0.2

In order to investigate the mesh size effect, several meshes have been constructed

	Characteristic element size (l_e)
Mesh 1	200mm
Mesh 2	100mm
Mesh 3	50mm
Mesh 4	20mm

The results of the analyses, shows the damage contours at 2 different times (Figure 1 and Figure 2).

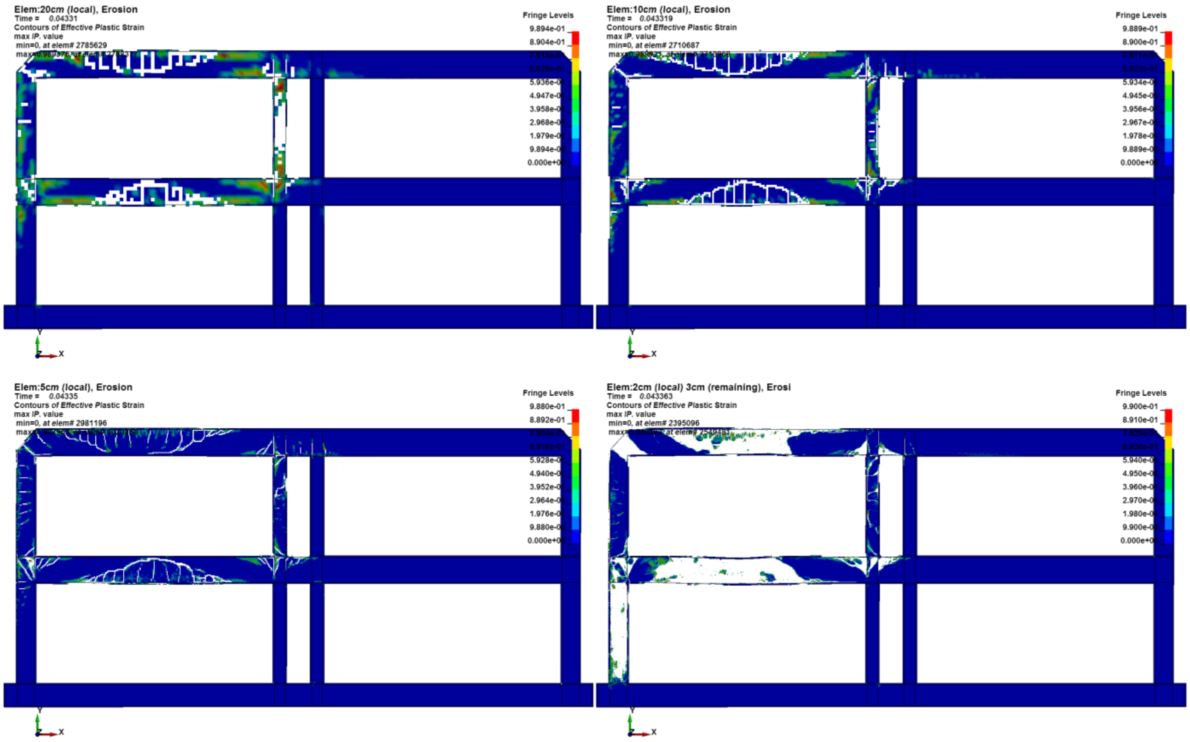


Figure 1Comparison of damage for 4 mesh sizes at=0.043ms. [top-left] Mesh1, [top-right] Mesh2, [bottom-left] Mesh3, [bottom-right] Mesh4.

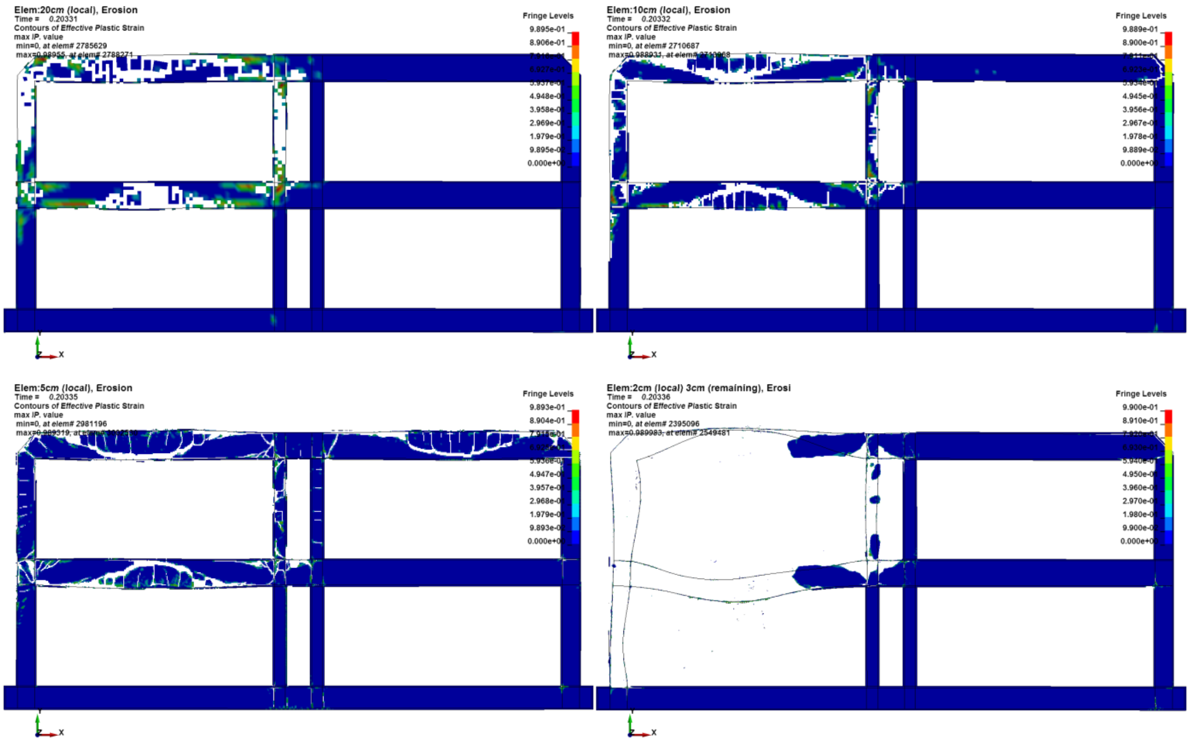


Figure 2Comparison of damage for 4 mesh sizes at t=0.20ms. [top-left] Mesh1, [top-right] Mesh2, [bottom-left] Mesh3, [bottom-right] Mesh4.

Several important observations based on these figures can be made:

- There is a severe mesh dependency
- Mesh 1 & mesh 2 appear to produce comparable results
- Mesh 3 & mesh 4 produce results that do not produce expected results.
- Mesh 3 & mesh 4 show an increasing amount of element erosion as element size reduces

The main goal of this paper is to present the source of this mesh dependence and possible solutions to this problem that will be researched in the future.

3. Modeling damage using a smeared crack approach & fracture energy regularization

This section will pose that the source of the observed mesh dependence lies in the modeling of the failure of the concrete.

Initially, the objective of the project was to evaluate concrete models for use with close-in blast and impact applications. To this end a concrete model has been selected from the extensive library of LS-DYNA concrete models

Material Model Name	**MAT_ID**	**Minimal user Input**	**Separate Damage Tension / Compression**	**Rate Dependent**
Soil and Foam Model	*MAT_005	No	No	No
Pseudo-Tensor	*MAT_016	Yes	No	No
Oriented Crack	*MAT_017	No	No	No
Geological Cap	*MAT_025	No	No	No
Concrete Damage	*MAT_072	Yes	No	Yes
Concrete Damage Rel3 (K&C)	***MAT_072R3**	**Yes**	Yes*$^{)}$	**Yes**
Brittle Damage	*MAT_096	No	No	No
Soil Concrete	*MAT_078	No	No	No
Winfrith Concrete	*MAT_084	Yes	No	Yes
Johnson Holmquist Concrete	*MAT_111	No	No	Yes
Schwer Murray Cap	*MAT_145	No	Yes	No
CSCM Concrete	***MAT_159**	**Yes**	**Yes**	**Yes**
RHT	***MAT_272**	**Yes**	Yes*$^{)}$	**Yes**

From the available models, a subset of 3 concrete models was selected that support

- Minimal input
  Such that the material model can be easily applied to concretes of different strengths
- Rate dependent behavior
  To account for rate effects due to high dynamic loadings
- Damage tracking
  in order to account for different behavior/damage in tension and compression

This investigation focusses on the CSCM Concrete model. It has been selected because of several distinguishing features.

- Separate damage parameter for ductile and brittle damage
- Damage does not reduce the ultimate strength, but reduces the bulk and shear stiffness of the material
- CSCM supports failure independent based on failure strain after maximum damage is reached (without resorting to *MAT_ADD_EROSION).

There is 1 similarity that the subset of 3 concrete models share, which is the treatment of damage. The CSCM model uses the smeared crack approach (Murray 2007-I, Murray 2007-II). The heterogeneous nature of concrete is modeled as a homogeneous material, in which cracks are modeled through a loss of strength (i.e. softening) of the material (see figure 3).

The internal energy that is associated with this softening behavior is usually referred to as the fracture energy (G_f). This energy is quantified per volume of the material. However, in FEM a continuum is discretized into elements, consequently larger elements (with a larger volume) have a larger fracture energy. The G_f should in fact remain constant, regardless of element size. In order to circumvent this issue, fracture energy regularization has been introduced, which scales the fracture energy with respect to element size in order to achieve mesh objective results.

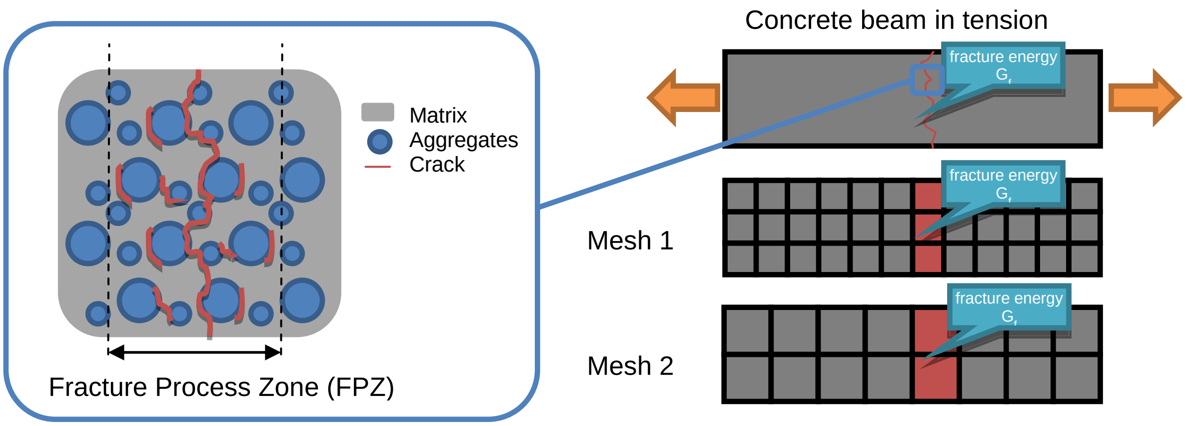


Figure 3 Smeared crack approach and regularization

G_f-regularization allows for a correct treatment of elements that vary in size, as long as the element is sufficiently large. When elements become small, errors can be introduced due to this regularization scheme. The next section will elaborate on the minimum element size at which regularization may be applied and the reasons for this minimum element size.

4. Errors due to regularization for small elements

Figure 3 shows a schematized representation of a crack in concrete. The section of concrete shows the matrix with aggregates and in it a main crack and surrounding microcracks. The width of the area containing the main crack and the microcracks is referred to as the fracture process zone (FPZ).

The implicit assumption in G_f-regularization is that an element wholly contains this FPZ. As long as an element is larger than width of the FPZ, regularization ensures that, at maximum, the G_f can be dissipated.

However, the regularization scheme breaks down if elements are smaller than the width of the FPZ. Regularization enforces that each element is able to dissipate the total G_f. As a consequence, of the smaller element, the FPZ is spanned by multiple element which can thus *each* dissipate the G_f (see figure 4).

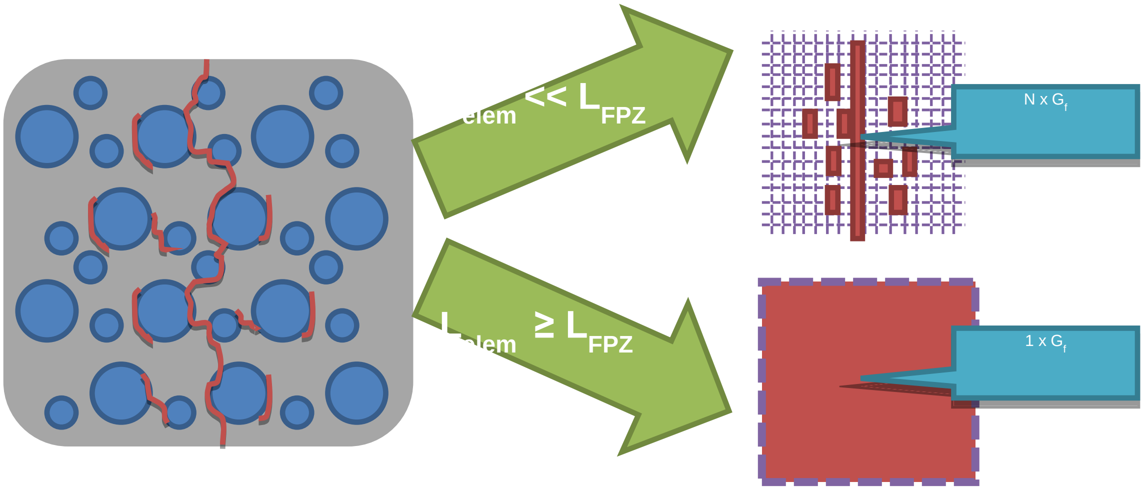


Figure 4Error due to regularization

The erroneous application of regularization causes the system to be able to take up more energy and thus results in an overestimate of the system's strength. This error has in fact already been described in 1981 (Bazant, 1983).

Using the CSCM material model, the error is demonstrated with a simulation of a concrete cylinder under compression.

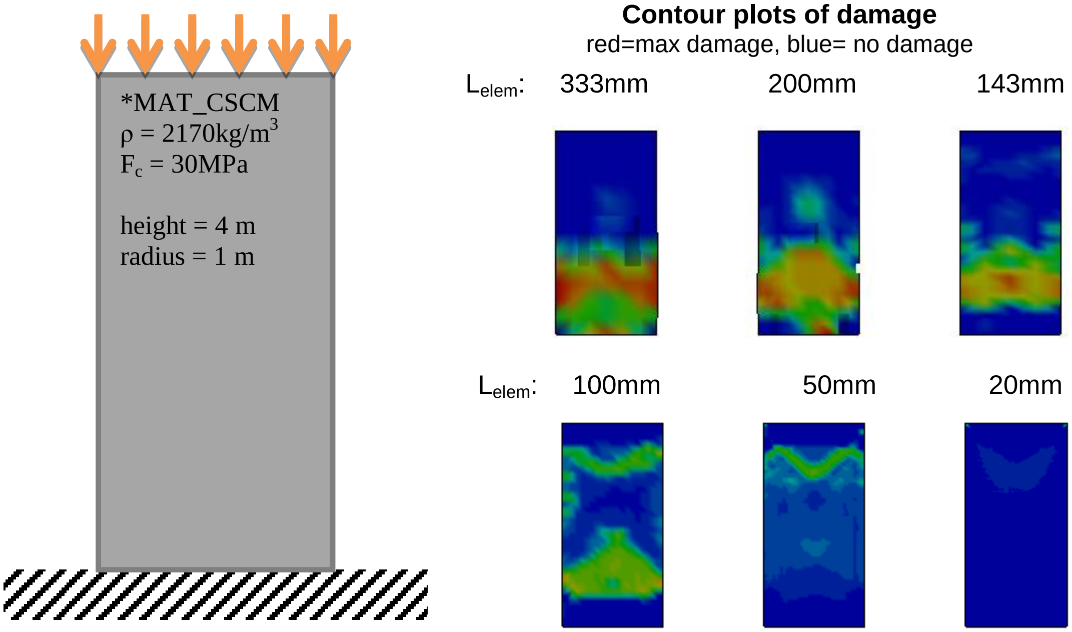


Figure 5Damage plots of concrete cylinder in compression.

Following from the theoretical predictions, this demonstration shows that smaller elements results in less damage in the system.

A similar exercise has been performed for a concrete cylinder in tension, resulting in the same conclusion. However, it did bring to light 1 additional observation, which is most visible in the total energy of the system (see figure 6).

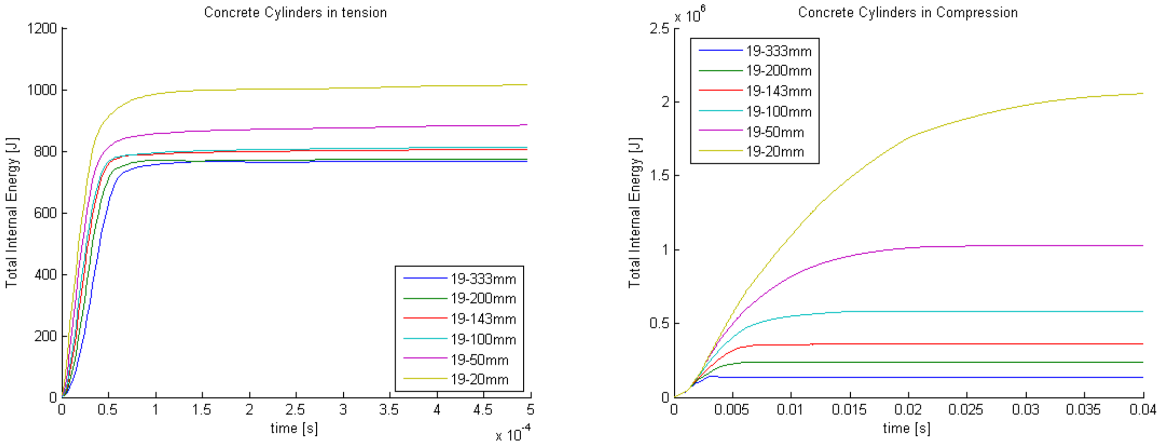


Figure 6Total internal energy for concrete cylinders in tension (left) and compression (right), for different element sizes

The total internal energy of the concrete cylinder shows the amount of energy that is taken up by the system. For the tension and compression analyses, only the mesh has been varied. Ideally all simulations should result in the same amount total internal energy.

For both situations (tension and compression) it can be seen that total internal energy increases for decreasing element size. However, where the tension analysis shows convergence (starting for element around 100~143 mm), the compression analysis only hints at convergence.

Apparently, in tension, the minimum element size is 100mm, corresponding to 5 times the aggregate size (given an aggregate size of 19mm). In compression, the minimum element size is at least 333mm, but most likely even larger. The larger element requirement in compression is a result of a larger FPZ in compression (Bazant, 1998).

When elements smaller than the minimum element size are used, it will become essential that they obtain information regarding the damage evolution in the FPZ. Such a nonlocal approach should ensure that the fracture energy (G_f) is dissipated in an area corresponding to the size of FPZ. Evaluation and implementation of such nonlocal methods will be a topic of future research.

5. Regularization in the other concrete models

The analysis so far has been performed using the CSCM model. In order to get an idea of how the other 2 (K&C, RHT) deal with regularization, the simulations of the concrete cylinders have also been performed using the 2 other concrete models. It should be mentioned that this in no way has been an extensive study of the theory of the other 2 concrete models, but merely an exercise.

The total internal energy for concrete cylinders in tension is given in figure 7. The situation for compression is given in figure 8.

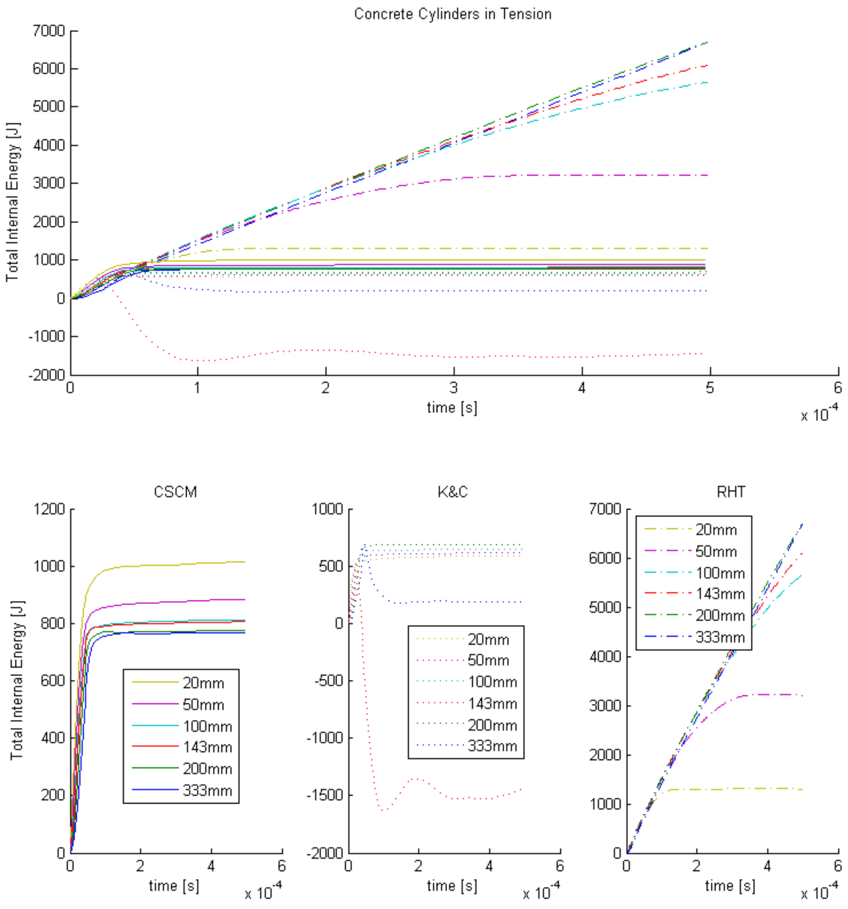


Figure 7Total internal energy in tensile loading, compared for 3 concrete material models (CSCM, K&C, RHT).

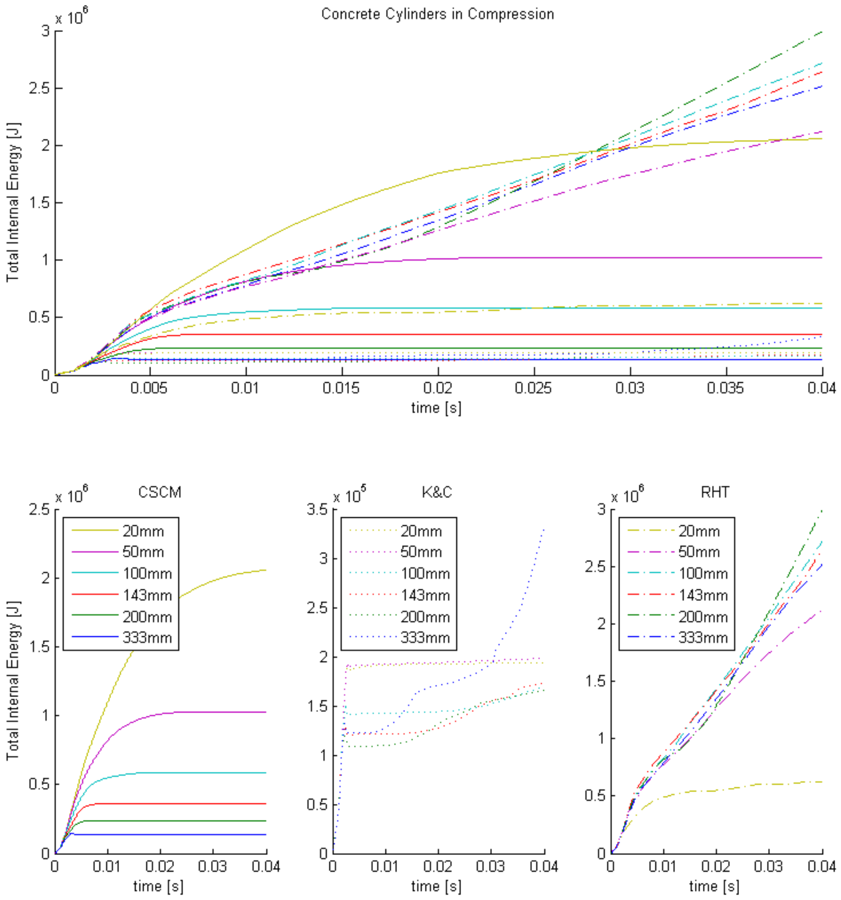


Figure 8Total internal energy in compressive loading, compared for 3 concrete material models (CSCM, K&C, RHT).

As previously shown, the CSCM model shown a divergence of the total internal energy as element size decreases. The K&C model initially shows some consistency in the results, however, results eventually diverge due to unknown reasons. The RHT has no regularization implemented and shows a severe explosion of the total internal energy.

A note should be made regarding the K&C model. The K&C model allows the user to specify the localization width (LOCWID). Below this element size, regularization is disabled. Disabling regularization will revert to the situation where fracture energy is dependent on the volume of the element, which in theory will always lead to an underestimate of the fracture energy and thus an underestimate of the structure's strength.

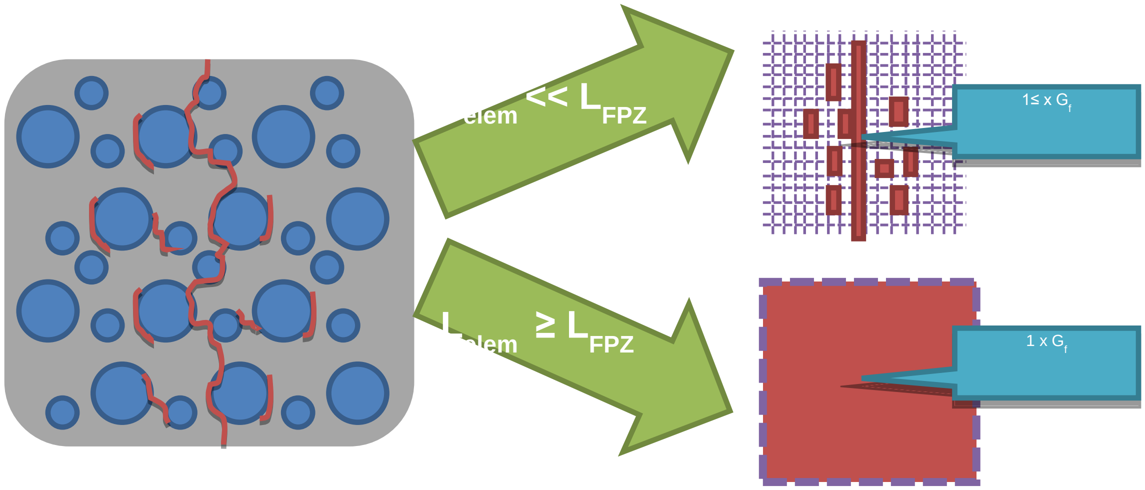


Figure 9Consequence of disabling regularization.

Disabling regularization may result in consistent results, but they are not physically correct. However, consistent results can always be tuned….

Mesh requirements for BLEVE application

Large elements may not be a problem if only the general response of structure is of interest. However, in the case of local effects, such as the close in BLEVE benchmark, small elements are required in order to accurately model the shockwave propagation through the structure.

In order to investigate the required element size, and present the necessity of small element for the desired application, a small study has been performed. Using a linear elastic material model with coefficients representative of concrete, the initial stages of the shockwave propagation in concrete are modeled.

6 slabs with a length of 7m and a thickness of 10cm are modeled (2D plane strain) with different meshes. The slabs will be loaded from the right side with a pressure load that is representative for a BLEVE loading.

	Characteristic element size [mm]	*N* elements thickness	*N* elements length
Mesh 6	100	1	7
Mesh 5	50	2	14
Mesh 4	25	4	28
Mesh 3	10	10	70
Mesh 2	5	20	140
Mesh 1	1	100	700

The pressure contours after 120μs have been plotted in figure 7.

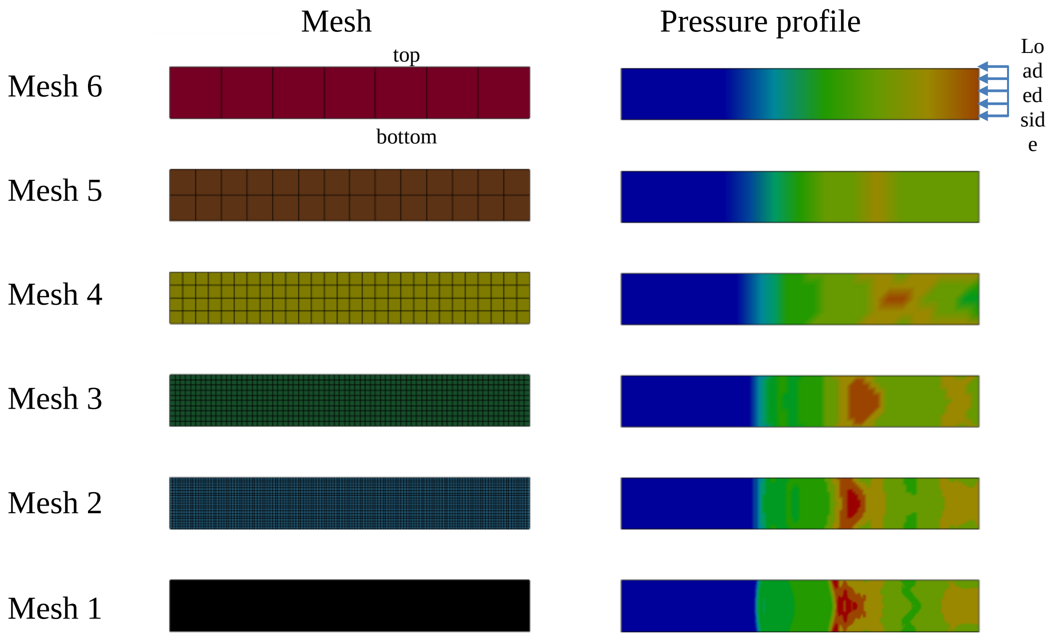


Figure 10 Different meshes for the concrete slabs and the pressure at t=120μs.

It may be observed (and is well known) that a certain element size is required to prevent dispersion of the introduced shock loading. In addition, a second stronger shock is observed in these simulations. This second shock originates from reflection from the top and the bottom of the slab, and only analyses with sufficiently fine resolution reveal this shock.

Based on the analyses, and under the assumption that the finest mesh (mesh 6) represents ideal results, the following table with characteristic results is obtained.

	Characteristic element size [mm]	Maximum Pressure [Pa]	% error w.r.t mesh 1	^{10}log(Effective strain rate) [1/s]	% error w.r.t. mesh 1
Mesh 6	1	243450	-13%	2.2	-36%
Mesh 5	5	236938	-16%	2.4	-30%
Mesh 4	10	251127	-11%	2.7	-22%
Mesh 3	25	271684	-3%	2.9	-15%
Mesh 2	50	285515	2%	3.0	-12%
Mesh 1	100	280934	0%	3.4	0%

Based on considerations regarding generated peak pressures and generated strain rates, the conclusions is drawn that a elements of at most 25mm should be used when analyzing the effects of the present BLEVE load. This element sizes shows an acceptable drop in peak pressure and has an acceptable error on the strain rate, whilst maintaining an element size that will result in acceptable runtimes.

Clearly the element size that is derived here is much less then the previously derived limit of 100mm in tension of >333mm in compression. This finding strengthens the conviction of finding a solution to overcome the minimum element size.

Conclusions & Future research at TNO regarding concrete modeling

TNO aims to improve the capabilities regarding the numerical analysis of high dynamic events. This analysis of close in blast in a concrete structure has been an essential step in the understanding of the numerical tools that are available. Understanding the limits of such tools is one of the key elements in performing accurate analyses.

This analysis has indicated the concrete models in LS-DYNA that utilize the smeared crack approach. Furthermore it has been shown that this approach places a requirement in the mesh. In tension, when performing numerical analyses on ‘normal’ concrete, the elements should not be smaller than 100mm. In compression even larger (>333mm) are required. The K&C model does present a workaround by disabling the regularization for small elements, however it still presents artifacts in the simulations and is no cure for the stated problem.

High dynamic events such as close in BLEVE blast, however, require a very fine mesh in order to be able to generate adequate predictions on the shock wave propagation and stress state of the system. In order to be able to combine the comprehensive concrete models with the small elements, one potential solution is the application of nonlocal models. In the future, a first investigation shall be made regarding *MAT_NONLOCAL. However several issue may prohibit its use;

- Computational burden of *MAT_NONLOCAL
- Unified treatment of compression and tension situations
- Treatment of cracks/gaps in the mesh

Possibly a custom implementation of a nonlocal model is required to overcome the presented situations.

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