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Comparison of different Constitutive Models for Concrete in ABAQUS/Explicit for Missile Impact Analyses

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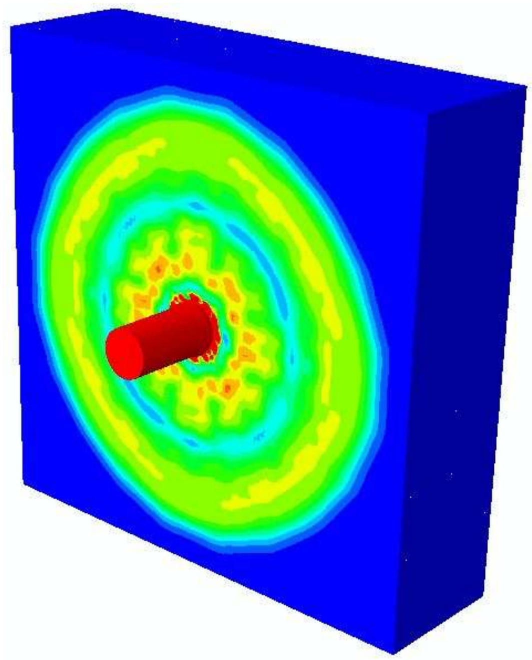
Safety of Present Nuclear Reactors Unit (SPNR)
Plant Operation Safety (POS)



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Content

1 Introduction

The issue of missile impacts on concrete containment buildings (CCBs) of nuclear power plants (NPPs) was subject to intensive research for the first time in the 1970s and early 1980s. During that period a number of missile impact tests, even on a large scale have been carried out, most notably the Meppen Tests in Germany and the Tests at Sandia National Laboratory in the USA. In both tests soft and hard missiles were impacted on large reinforced concrete slabs resembling the CCBs of NPPs build at that time. In parallel quite a number of computational analyses have been performed to predict the results of these tests. For these analyses either empirical formulas or relatively coarse finite difference (FD) or finite element (FE) models even with load curves were used. Due to the limitations of these models the possibility to predict the outcome of missile impact tests was quite difficult. Today quite a number of advanced computational methods and methodologies are available for impact analyses and as a result the issue of missile impact testing has reached a significant level of interest inside the nuclear community again.

The topic of missile impacts on CCBs of NPPs was subject of a panel discussion during the previous SMiRT20 Conference, held in Espoo, Finland in August 2009 [1]. During this panel discussion IRSN and OECD-NEA called for the benchmark project "Improving Robustness Assessment Methodologies for Structures impacted by Missiles (IRIS)". The objective of this benchmark project is to issue recommendations for the modelling of mechanical effects of missile impacts on concrete containment structures. The benchmark project will start in January 2010 and will have a duration of one year. It runs under the subgroup on concrete of the IAGE. Each participating party is requested to computationally model the new missile impact tests by VTT/IRSN (performance in first half of 2010) and some of the Meppen Tests. The participating organisations will present and exchange their results in a workshop in December 2010 and will issue a state-of-the-art report on the subject in 2011 based on the results of the participants. JRC-IE will participate in the benchmark project IRIS.

This EUR report describes the first own missile impact analyses performed at JRC-IE in order to get familiar with the topic and as a preparation for the benchmark project IRIS. The analyses are performed with the FE solver ABAQUS/Explicit [2] and traditional Lagrangian formulations for both the missile and reinforced concrete slabs are used. Two different build-in constitutive models for concrete in ABAQUS/Explicit, the Brittle Cracking Model and the Concrete Damaged Plasticity Model [2], are used and their suitability and limitations for missile impact analyses are explored. A hard and a soft missile are used for both constitutive models and sensitivity studies related to the initial missile velocity are performed.

2 Missile Impact Tests

2.1 Large-Scale Missile Impact Tests

As mentioned in the introduction already the Meppen Tests and the Tests at Sandia National Laboratory represent two series of large scale missile impact tests to assess the strength of CCB designs of NPPs against air plane crashes. The Meppen Tests were performed in the late 1970s and early 1980s near the German town of Meppen (this is where their name originates from) by the German construction company HOCHTIEF and the German electrical & electronics company SIEMENS to test the CCB design of German NPPs against the impact of small military aircrafts [3,4,5]. Two series of tests were carried out. In the first tests series, which was entirely performed by HOCHTIEF, highly deformable missiles were impacted against rigid targets. The purpose of the first test series was to investigate the generated load time curves [3,4,5]. In the second test series the same missiles were impacted on reinforced concrete slabs, which resembled the concrete hull of a typical NPP build at that time. The missiles used in the Meppen Tests were made of mild steel (mild steel St 37), had an outer diameter of 600 mm and a total length of approximately 6 m. Thus they resembled the body of a typical military aircraft. The wall thickness of the missile varied between 7 mm in the front to 10 mm in the rear [3]. The reinforced concrete slabs used in the Meppen Tests were rectangular in shape with the dimensions 6.5 m × 6 m and had a thickness from 50 mm to 90 mm. The velocities of the missiles varied from 172.2 m/s to 257.6 m/s.

The missile impact tests of Sandia National Laboratories involved small scale, intermediate scale and full scale tests using reinforced concrete slabs of dimensions 1.5 m × 1.5 m, 2.5 m × 2.5 m and 7 m × 7 m respectively [6]. The thicknesses of the slabs varied between 60 mm to 350 mm, 350 mm to 600 mm and 900 mm to 1600 mm respectively [6]. Test series with rigid and deformable missiles were performed for each of the three reinforced concrete slabs. The deformable missiles were cylindrical tubes with a diameter of 101 mm and a length of 317 mm for the small-scale tests, cylindrical tubes with a diameter of 300 mm and a length of 983 mm for the intermediate-scale tests and cylindrical tubes with a diameter of 760 mm and a length of 2378 mm for the large-scale tests [6]. The rigid missiles were massive steel/aluminium cylinders with a diameter of 101 mm and a length of 110 mm for the small-scale tests. For the intermediate-scale tests cylindrically shaped steel tubes with a massive thick front plate were used for the rigid missiles. They were 300 mm in diameter and had a length varying between 351 mm and 498 mm. For the large-scale tests real aircraft engines, i.e. a GE-J79 engine, were used as rigid missiles [6]. The velocities of the missiles varied between 83 m/s and 217 m/s for the small-scale tests, 99 m/s and 251 m/s for the intermediate-scale tests and 205 m/s and 215 m/s for the large-scale tests [6].

In summary deformable missiles representing the body of a typical military aircraft and/or extremely stiff missiles representing the engine of an aircraft are used for large-scale missile impact tests. They are impacted on reinforced concrete slabs with velocities, which resemble typical velocities of aircrafts.

2.2 Small-Scale Missile Impact Tests

Normally large-scale missile impact tests are expensive to perform, so the number of these tests performed so far is quite limited. Additionally often strike forces are the initiators of such tests and so their results are often not publically available. Instead smaller tests on laboratory scale are carried out. Both the reinforced concrete slab and the missile are considerably scaled down in their dimensions. One example for these lab scale tests are the missile impact tests by Hanchak et al. [7]. For these tests rectangular shaped reinforced concrete slabs of the dimensions 610 mm × 610 mm × 178 mm are used. The slabs contain three layers of steel reinforcement in thickness direction with a distance of 76.2 mm from each other in both horizontal directions (see Figure 1). The diameter of the steel bars is 5.69 mm. Figure 2 shows the missile Hanchak et al. were using for their tests. It is a 25.4 mm massive calibre steel projectile with an ogive nose and a total length of 143.7 mm.

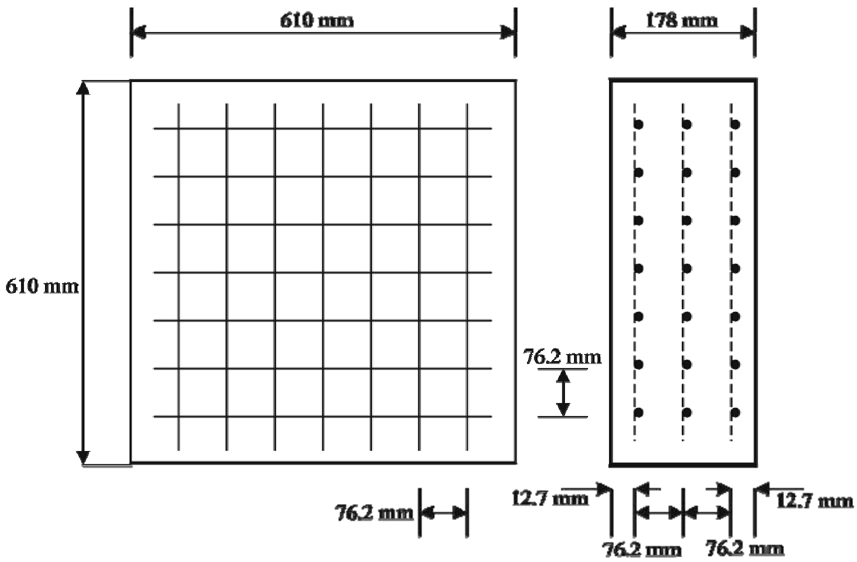

Fig 1: Reinforced concrete slabs used in the missile impact tests of Hanchak et al. [7].

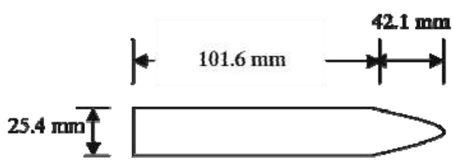

Fig. 2: Massive calibre steel projectile used by Hanchak et al. [7].

The tests of Hanchak et al. are typical for lab-scale missile impact tests both concerning the dimensions of the reinforced concrete slab and also with regards to the size and material of the missile. The computational analyses described in this report are based on the tests of Hanchak. Additionally to the hard missile in Figure 2 also FE analyses with a soft missile are performed (see Chapter 4).

3 Typical Failure Modes and Energy Balance

There are in principal two overall response failure modes for reinforced concrete walls or buildings impacted by a missile: Flexural failure or punching shear failure. Both failure modes are caused by the elastic-plastic response of the reinforced concrete structure. They are displayed in Figure 3.

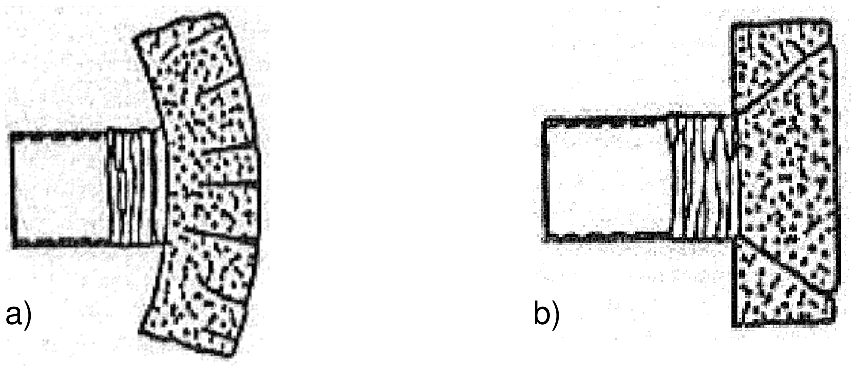

Fig. 3: a) Flexural failure and b) punching shear failure.

At the flexural failure mode the reinforced concrete slab bends strongly due to the impact of the missile. The front side of the reinforced concrete slab, where the missile impacted on, is compression loaded. The back side is subject to tension loading, which leads to the formation of cracks in thickness direction of the reinforced concrete slab. In the worst case the cracks go through the entire thickness of the reinforced concrete slab leading eventually to complete perforation. At the punching shear failure mode a shear cone forms inside the reinforced concrete slab as indicated in Figure 3b. In the worst case the shear cone is punched out of the reinforced concrete slab. In contrast to flexural failure, where the concrete slab fails due to excessive tension stresses, at punching shear failure the concrete slab fails due to excessive shear stresses.

The likelihood if flexural failure or punching shear failure is more likely depends upon the kind and velocity of the missile and the strength of the reinforcement inside the concrete slab. For a strong reinforcement flexural failure is more likely, for a weaker one punching shear failure. In case of a soft missile flexural failure of the reinforced concrete slab is more likely and in case of a hard missile (with an ogive nose) punching shear failure becomes more likely. For lower impact velocities flexural failure is more likely, for high impact velocities punching shear failure becomes more likely.

Beside the two overall response failure modes four local damage failure modes exist, which are displayed in Figure 4. They are caused by stress wave response and usually always occur in conjunction with the two overall response failure modes. At surface failure concrete falls off the impacted wall or structure at and around the impact zone. The penetration depth of the missile is low. When spalling occurs the missile penetrates deeper into the concrete wall or structure and significantly more material falls off compared to surface failure. In case of scabbing additionally concrete particles spall off the backside of the impacted wall or structure. Perforation represents the worst case. The missile moves through the impacted wall or structure. Perforation is normally always accompanied by spalling and scabbing.

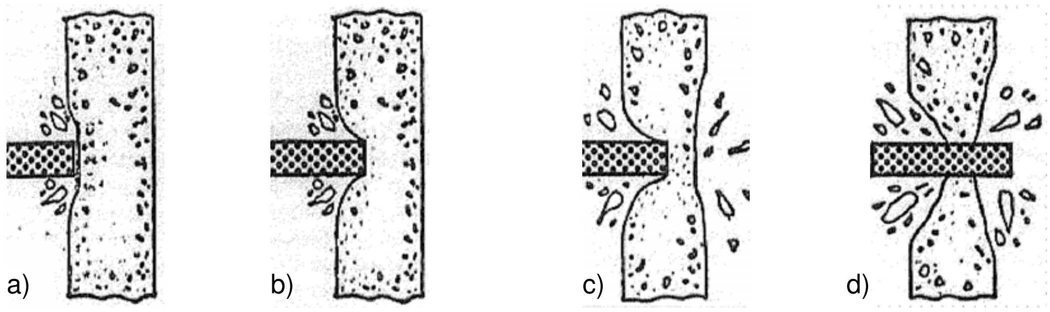

Fig. 4: Local damage failure modes: a) Surface failure, b) spalling, c) scabbing and d) perforation.

During a missile impact on a structure there is always a huge transfer of mechanical energies involved. So in order to evaluate the results of numerical missile impact analyses correctly a look at the energy balance should always be the first step. The missile and the concrete slab together can be seen as one mechanical system. In the beginning before the impact there is only the kinetic energy of the missile. While the missile impacts into the concrete structure it is usually slowed down significantly, i.e. it looses huge portions of its kinetic energy. Most of the lost kinetic energy is absorbed as strain energy (elastic and plastic strain energy) in the reinforced concrete slab and in the missile. This is visible as deformation of slab and missile after the impact. Normally also parts of the concrete slab are destroyed, so part of the kinetic energy of the missile is transformed into damage energy. A smaller part of the kinetic energy of the missile is transferred to the concrete slab as kinetic energy. This is visible as vibrations of the concrete slab that typically occur as a result of a missile impact. Then normally also part of the initial kinetic energy of the missile will dissipate due to viscous damping inside the missile and the reinforced concrete slab. So the energy balance of a missile impact on a concrete slab can be written as follows:

$$E_{kin0}^{M} = E_{kin1}^{M} + E_{str1}^{M} + E_{kin1}^{S} + E_{str1}^{S} + E_{dam1}^{S} + E_{vis} \quad , \tag{3.1}$$

with E_{kin0}^{M} = kinetic energy of missile before impact
E_{kin1}^{M} = kinetic energy of missile after impact
E_{str1}^{M} = strain energy of missile after impact
E_{kin1}^{S} = kinetic energy of concrete slab after impact
E_{str1}^{S} = strain energy of concrete slab after impact
E_{dam}^{S} = energy dissipating due to damage of concrete
E_{vis} = energy dissipating due to viscous damping

The way how the initial kinetic energy of the missile is allocated among the different forms of energy in equation (3.1) after the impact depends upon the type of the missile (hard or soft), its velocity and the reinforcement of the concrete slab. When e.g. a concrete structure with a strong reinforcement is subject to an impact of a soft missile with a high velocity most of the initial kinetic energy of the missile will end up as strain (deformation) energy of the missile.

Beside the real physical energies artificial energies might occur during a numerical analysis. When a numerical analysis, i.e. FE analysis, is carried out where individual finite elements are likely to be heavily distorted (deformed) so that they might end up having no volume anymore, FE solvers usually add an artificial stiffness to these finite elements in order to avoid excessive distortions and compression of elements. These artificial stiffnesses are visible in the results of FE analyses as artificial energies. They are not real physical energies, but can build-up during FE analyses to amounts comparable to real physical energies. So the results of FE analyses where heavy distortion or compression of individual finite elements is likely should be critically reviewed. In order to account for the artificial energies E_{art} equation (3.1) has to be rewritten as

$$E_{kin0}^{M} = E_{kin1}^{M} + E_{str1}^{M} + E_{kin1}^{S} + E_{str1}^{S} + E_{dam}^{S} + E_{vis} + E_{art} \quad . \tag{3.2}$$

4 FE Models and Constitutive Models

4.1 FE Models and basic Material Properties

Figure 5 shows the FE model with the hard missile and Figure 6 the one with the soft missile. The mesh for the concrete slab is the same in both cases and standard linear solid elements (HEX8, ABAQUS elements C3D8/C3D8R, Lagrangian formulation) are used. The solid elements have a dimension of approximately 6 mm in all three directions in space, making the mesh of the concrete slab extremely fine.

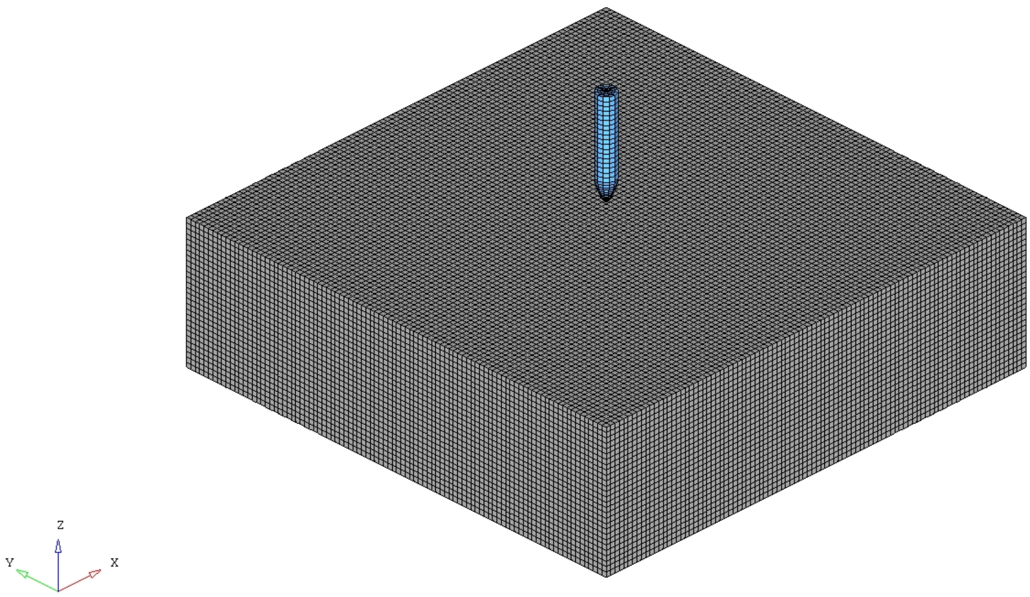

Fig. 5: FE model with hard missile.

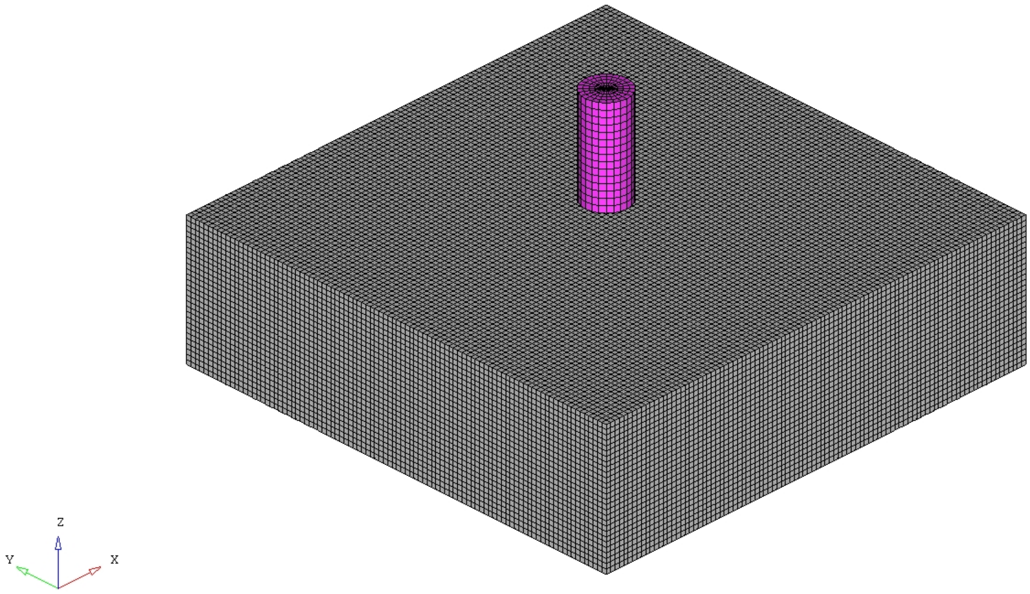

Fig. 6: FE model with soft missile.

The reinforcement of the concrete slab is modelled with truss elements as displayed in Figure 7 (ABAQUS elements T3D2). The truss elements are coupled with the HEX elements of the concrete slab with the *EMBEDDED ELEMENTS function of ABAQUS [2]. With this function the nodes of a truss element are kinematically constrained to the nodes of the solid element in which it is located. This means that the displacement of the node of the truss element is an average value of the displacements of the neighbouring nodes of the solid element in which the truss element is embedded.

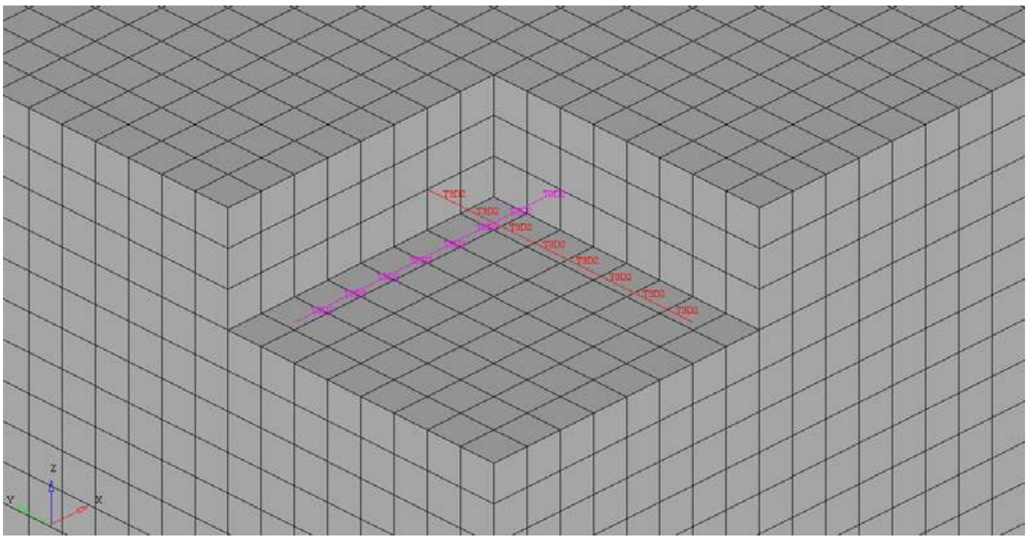

Fig. 7: Modelling of reinforcement in concrete slab.

Figure 8 shows the FE models of the hard and soft missile. The hard missile is modelled as a rigid body, in order to avoid excessive simulation times caused by heavy distortion of the elements at the projectile nose. The soft missile is modelled with standard shell elements (ABAQUS elements S3R and S4R) with 3 mm thickness.

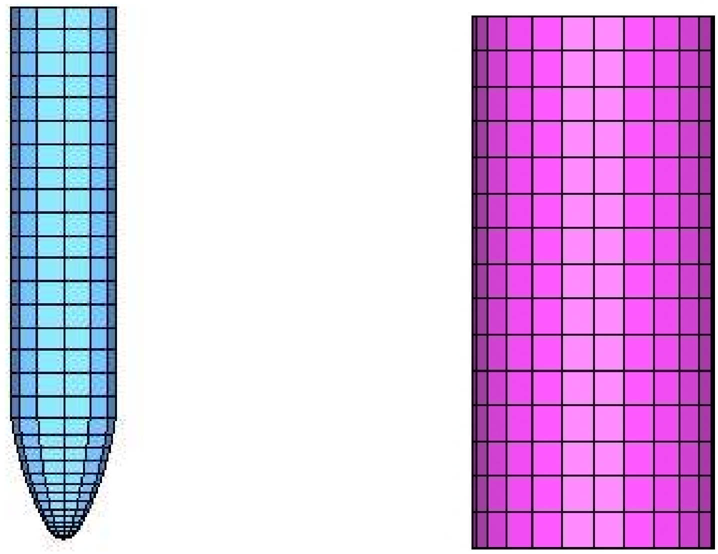

Fig. 8: FE models of hard and soft missile.

Table 1 summarizes the type and number of elements, the number of nodes and the number of degrees of freedom (dof) for each component.

Table 1: Element type and number of elements, nodes and dof for each component.

Component	FE type	No. elements	No. nodes	No. dof
Concrete slab	HEX8 (C3D8/C3D8R)	258048	272861	818583
Rebars	Truss (T3D2)	4608	4656	13968
Hard missile	Rigid element	1	1	6
Soft missile	Shell elements (S3R, S4R)	600	578	2890

Table 2 shows the basic material properties used for the concrete, the reinforcement and the soft missile. It is assumed that the reinforcement and the soft missile are made of mild steel St37. The values for the mass density, E-Moduli and Poisson ratios for both materials are taken from the article of Teng et al. [8]. The yield stress values for concrete are taken from the article of Chopra and Chakrabarti [9,10]. The yield and tensile strength for the mild steel St37 are taken from [11]. The stress-strain curve displayed in Figure 9 is created using these values.

Table 2: Basic material properties used for the analyses.

Material	Mass density ρ [kg/m^3]	E-Modulus [MPa]	Poisson ratio ν	Yield stress compression [MPa]	Yield stress tension [MPa]
Concrete	2565	20800	0.175	13.0	2.9
Steel	7850	199000	0.3	220.0	220.0

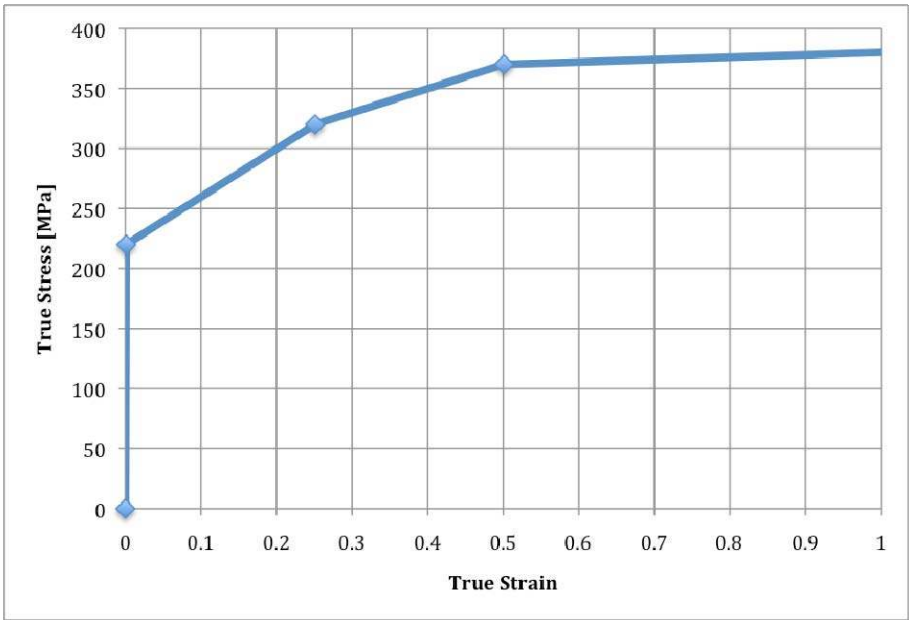

Fig. 9: Stress-strain-curve for mild steel St37 used for reinforcement and soft missile.

4.2 Brittle Cracking Model for Concrete

As mentioned already two different constitutive models for concrete implemented in ABAQUS/Explicit are used for the analyses described in this report. One of the two constitutive models is the Brittle Cracking Model (ABAQUS command: *BRITTLE CRACKING) [2]. The Brittle Cracking Model is designed for cases where the overall material behaviour is dominated by tensile cracking. It assumes that the compressive behaviour of concrete is always linear elastic, which does not resemble reality and is a weakness of the model. It is most accurate in applications where the brittle behaviour dominates such that the assumption that the material is always linear elastic in compression is adequate. This is not really the case for missile impact analyses, since the reinforced concrete slab is compressed very heavily, especially when a soft missile is used. On the other hand the Brittle Cracking Model allows the removal of elements based on a brittle failure criterion (ABAQUS command: *BRITTLE FAILURE) avoiding in theory large distortions of elements. Figure 10 displays the stress-strain-curve for the Brittle Cracking Model as used for the analyses. It is based on the material properties of Chopra and Chakrabarti [9].

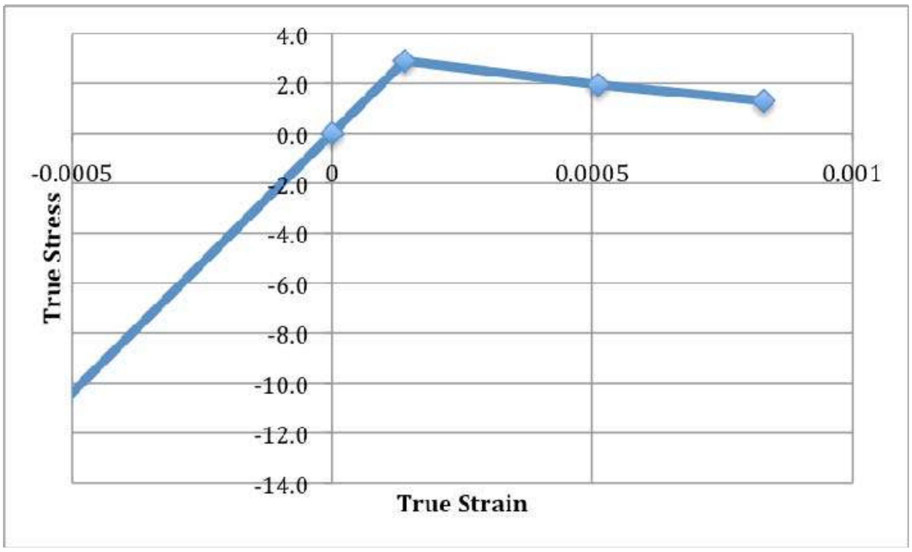

Fig. 10: Stress-strain-curve for the Brittle Cracking Model for Concrete.

4.3 Concrete Damage Plasticity Model

The Concrete Damaged Plasticity Model (ABAQUS command: *CONCRETE DAMAGED PLASTICITY) uses the concept of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behaviour of concrete. In contrast to the Brittle Cracking Model it allows the definition of strain hardening in compression and can be defined to be sensitive to the straining rate, which resembles the behaviour of concrete more realistically. The Concrete Damaged Plasticity Model is designed for applications in which concrete is subject to cyclic loading with alternating tension compression loading, e.g. seismic problems. The model allows stiffness recovery during cyclic loading reversals. In contrast to the Brittle Cracking Model the Concrete Damaged Plasticity Model does not contain a failure criterion and thus does not allow the removal of elements during the analyses. This makes it difficult to model missile impact phenomena where perforation of the missile through the reinforced concrete slab is most likely, i.e. high initial missile velocity and weak reinforcement. On the other hand the Concrete Damaged Plasticity Model may be used in conjunction with adaptive meshing (ABAQUS command: *ADAPTIVE MESH). Adaptive meshing means that the impacted zone of the concrete slab is re-meshed regularly during the analyses in order to avoid heavy distortion of the elements. This allows completion of the analyses even to relatively high deformation rates.

Figures 11 and 12 show the stress-strain-curves for the Concrete Damaged Plasticity Model for compression and tension loading respectively. The curves are based on the material properties of Chopra and Chakrabarti [9,10], which are designed to model the behaviour of concrete structures under seismic loading.

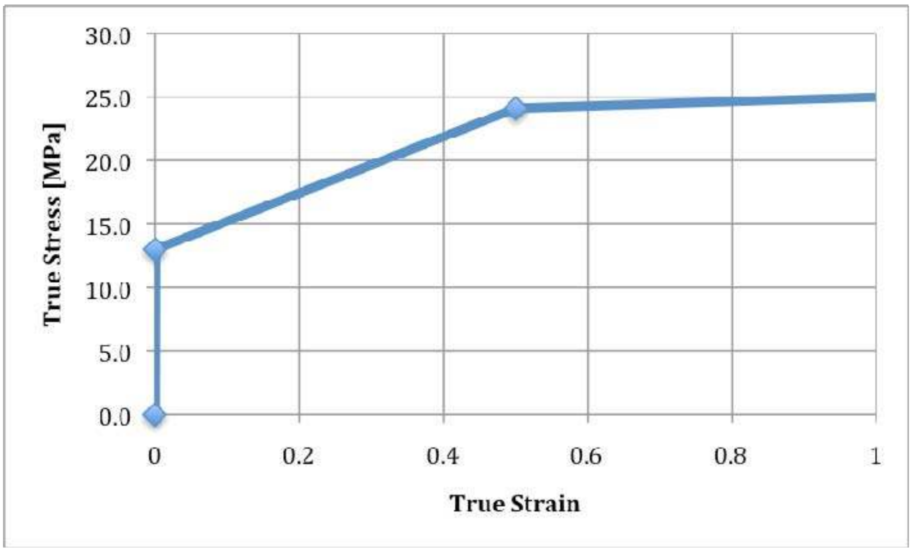

Fig. 11: Stress-strain-curve for concrete under compression loads.

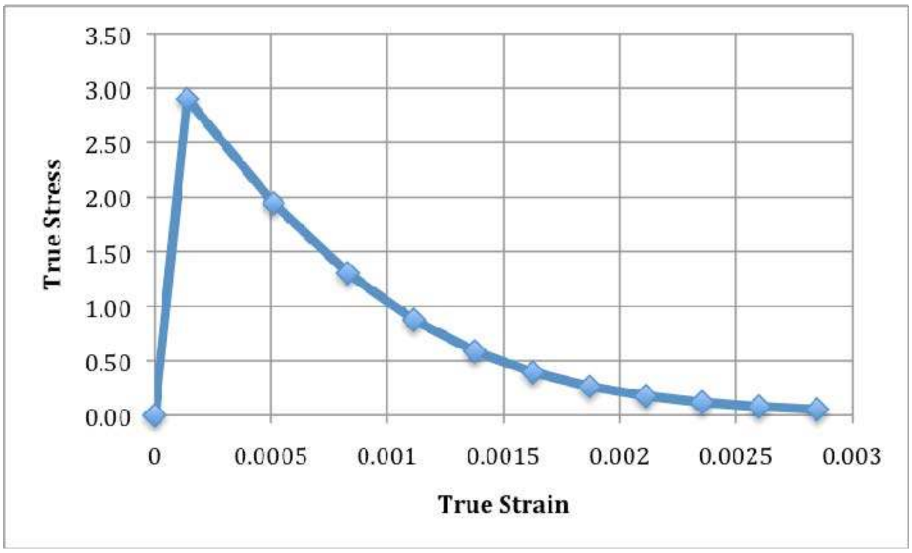

Fig. 12: Stress-strain-curve for concrete under tension.

4.4 Boundary Conditions and initial Missile Velocities

The reinforced concrete slab is fixed along node paths parallel to its edges on its backside as indicated in Figure 13 in the flight direction of the missile (global Z axis).

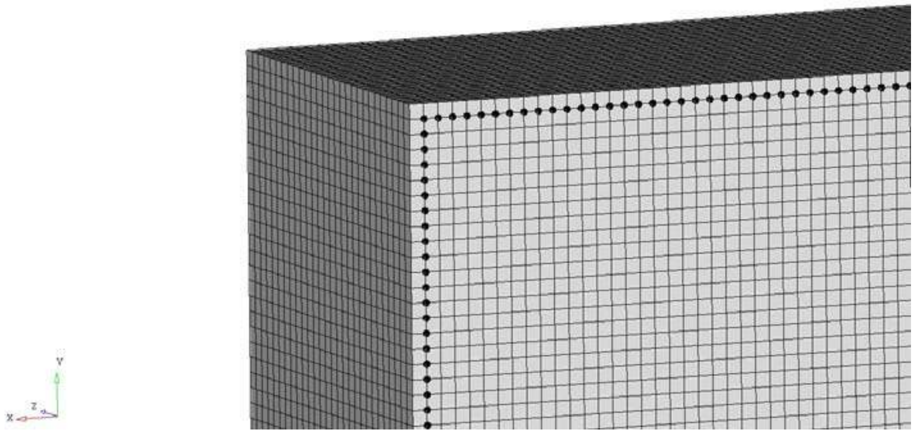

Fig. 13: Boundary conditions of reinforced concrete slab.

For both described constitutive models FE analyses with hard and soft missile are performed with various initial velocities of the missile. The range of initial velocity values ranges from relatively slow (75 m/s) to extremely high (500 m/s). Beside these two velocity values analyses are performed for 150, 250 and 400 m/s, where as 250 m/s is taken as the reference value for all the analyses in accordance with the known missile impact tests [3,4,5,6]. The range of missile velocities resembles the velocity values used in the analyses by Teng et al. [8]. The initial velocities are applied to the centre node of the hard missile (rigid body!) and all the nodes of the soft missile.

Concerning the interaction between missile and reinforced concrete slab general contact is used including all the inner surfaces of the concrete slab (ABAQUS commands: *CONTACT and *CONTACT INCLUSIONS, see ABAQUS input files in the Appendix).

5 Results of FE Analyses

5.1 Results with Concrete Cracking Model

Figure 14 shows the van Mises stress distribution on the front and backside of the reinforced concrete slab after the impact of a hard missile with an initial velocity of 250 m/s. The figure shows no evidence for any loading and vibration of the reinforced concrete slab as a consequence of the impact of the missile. The missile perforates through the reinforced concrete slab quite easily without generating any stresses inside the concrete slab. The overall stress distribution inside the reinforced concrete slab stays at zero level after the impact of the missile and thus is unrealistically low. For the other missile velocities mentioned in section

4.4 the results are the same: Fast perforation of the missile through the concrete slab without any trace of loading and vibration.

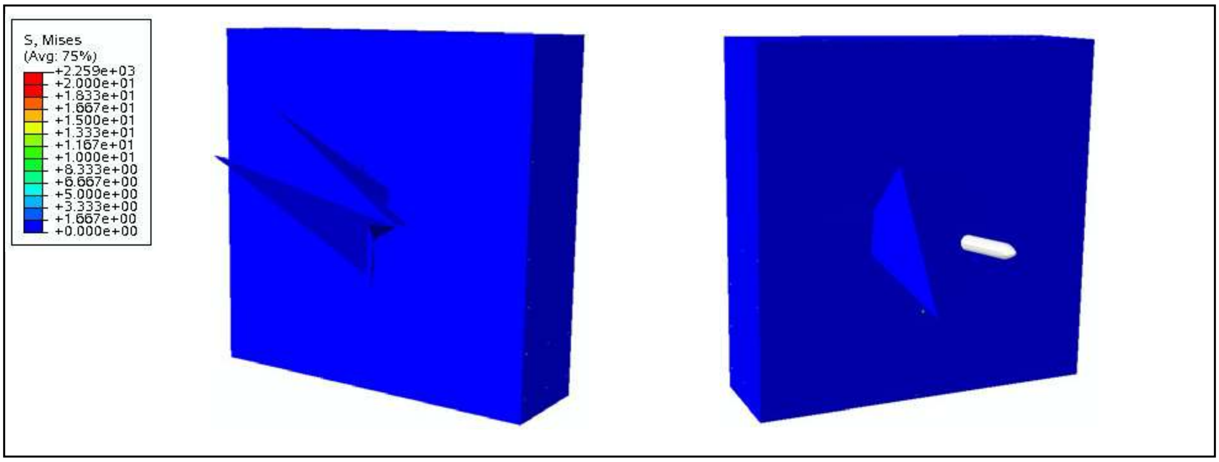

Fig. 14: Van Mises stress distribution of concrete slab after impact of hard missile with v=250 m/s.

The observed results indicate that finite elements of the reinforced concrete slab are removed rather quickly from the FE model during the analyses before reasonable strains and stresses build up in the concrete slab. Thus the value for the brittle failure strain, which determines when an element has failed and is removed from the FE model, is too low. The value for the brittle failure strain has been set to 10^{-6} to achieve completion of the analyses. For higher and more realistic brittle failure values in the range of 10^{-3} the analyses have not completed, because of high distortion of elements. Already for a brittle failure strain value of 10^{-6} there are quite a number of distorted elements leaving the reinforced concrete slab as indicated in Figure 14 giving the concrete slab quite a high kinetic energy. Figure 15 displays the energy balance for the missile impact analysis shown in Figure 14. According the energy balance the missile keeps approximately 75% of its initial kinetic energy and the 25% it loses is transferred to the concrete slab as kinetic energy. The strain energy of the concrete slab is negligible, which is in contrast to the results of the known missile impact tests [3,4,5,6,7]. So in summary the energy balances of the analyses with a hard missile in connection with the Concrete Cracking Model of ABAQUS/Explicit are not realistic.

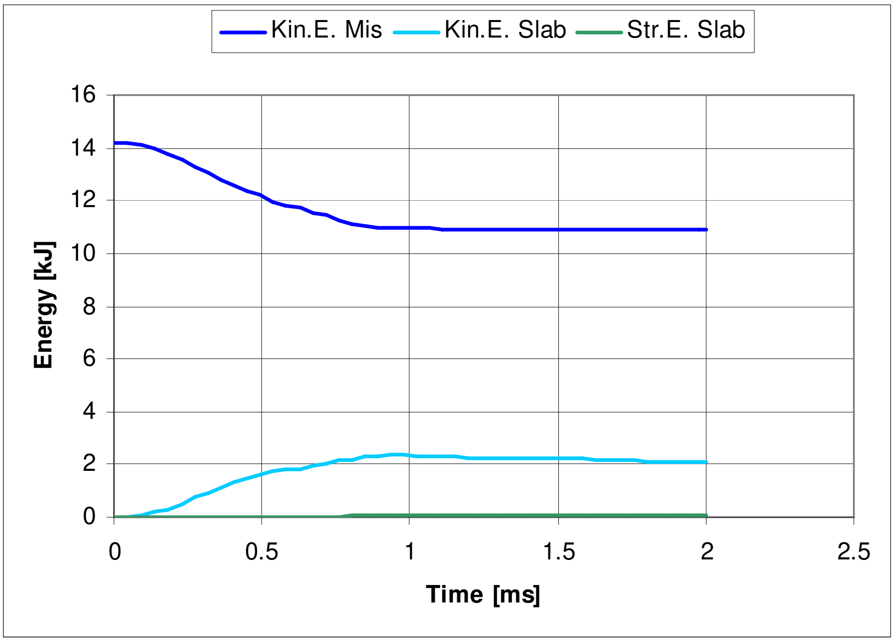

Fig. 15: Energy balance for hard missile with v=250 m/s.

For the soft missile the results are similar to the ones for the hard missile and thus also physically questionable. The soft missile penetrates deeply into the reinforced concrete slab, which by itself is not in accordance with the results of the known missile impact tests [3,4,5,6,7]. While penetrating through the concrete slab the soft missile induces no strains and stresses inside the concrete slab as Figure 16 shows.

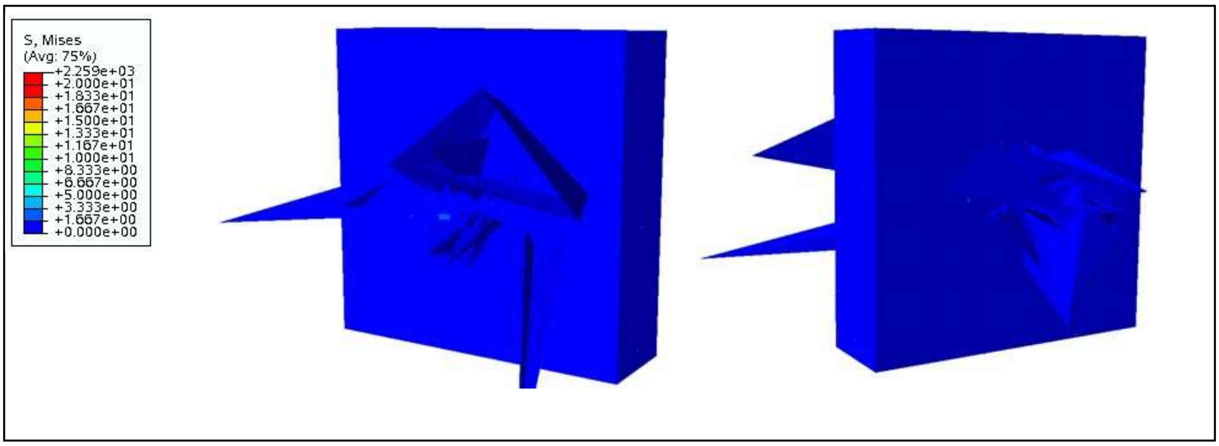

Fig. 16: Van Mises stress distribution of concrete slab after impact of soft missile with v=250 m/s.

Figure 17 displays the energy balance. In contrast to the hard missile nearly all of the initial kinetic energy of the missile is absorbed, but mostly in the form of kinetic energy of the concrete slab. Quite some initial kinetic energy of the missile is transformed into strain energy of the missile, which is reasonable. As for the hard missile before the strain energy of the concrete slab is negligible thus it does not deform at all.

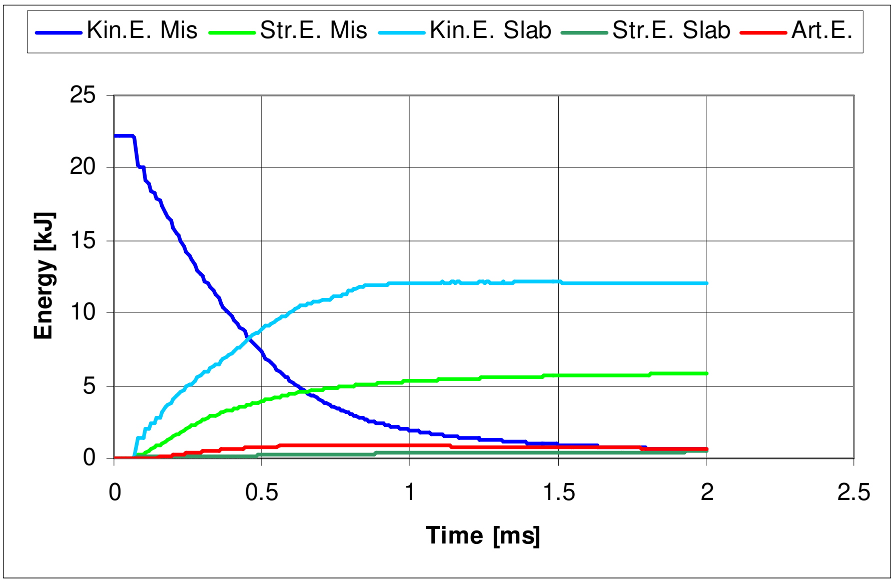

Fig. 17: Energy balance for soft missile with v=250 m/s.

In conclusion the Concrete Cracking Model in ABAQUS/Explicit does not seem to be a suitable constitutive model to model missile impacts on reinforced concrete slabs when solid 3D meshes are used. The brittle failure strain has to be set to extremely low values in order to achieve a completion of the analyses. The hard missile perforates through the reinforced concrete slab while keeping most of its initial kinetic energy. The soft missile loses all its initial kinetic energy, but also penetrates quite deeply into the reinforced concrete slab, which does not reflect the outcome of the known missile tests. For both kinds of missiles the largest proportion of the lost initial kinetic energy of the missile ends up as kinetic energy of the concrete slab and not as strain energy of concrete slab and missile (in case of soft missile) as one would expect. Quite some elements are heavily distorted and there are virtually no signs for any loading in the form of strains/stresses of the reinforced concrete slab due to the missile impact.

5.2 Results with Concrete Damaged Plasticity Model

5.2.1 Results with hard Missile

Figures 18 and 19 show the van Mises stress distribution on the front and backside of the reinforced concrete slab at various moments in time for the impact of the hard missile with an initial velocity of 250 m/s. In contrast to the Concrete Cracking Model in the section before the Concrete Damaged Plasticity Model clearly provides loading in the form of strains/stresses in the reinforced concrete slab due to the missile impact. Figures 18 and 19 also show very nicely the propagation of the stresses inside the concrete slab in the form of waves, which is a clear indication for vibrations of the concrete slab as it should be.

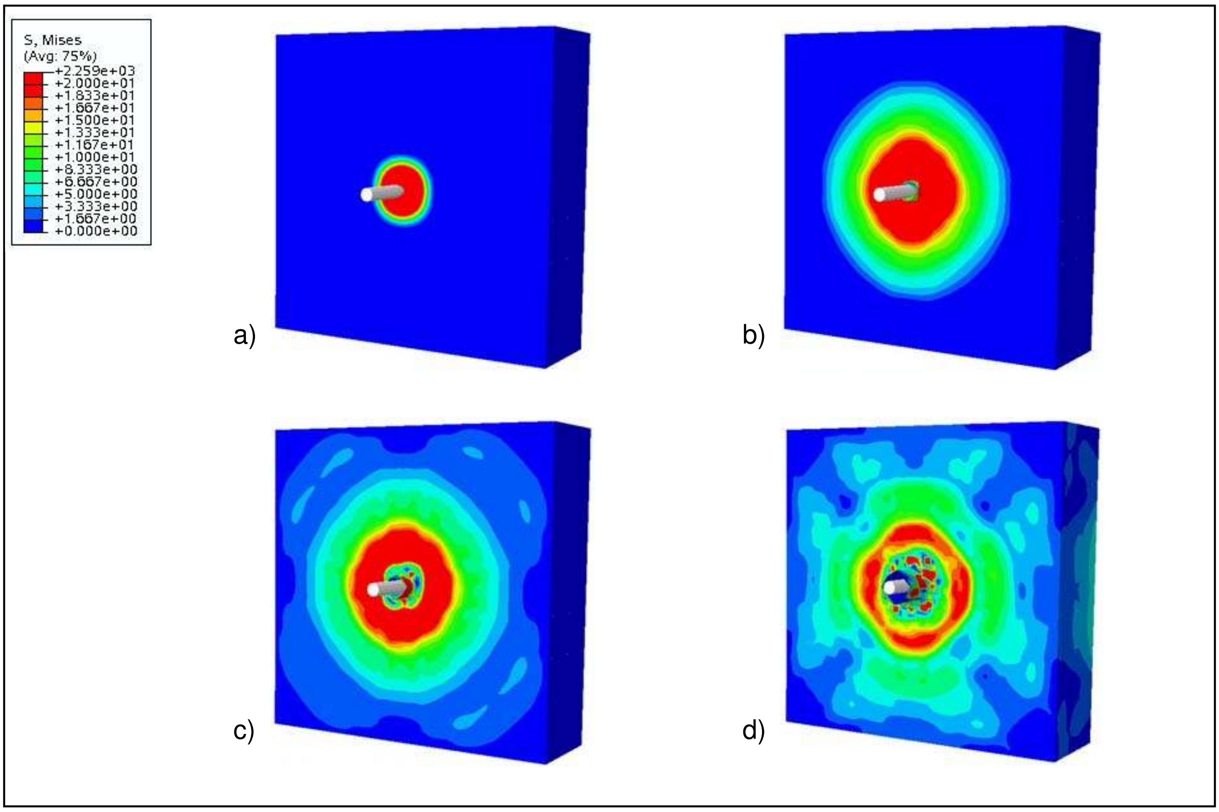

Fig. 18: Van Mises stress distribution on front side of concrete slab a) 0.1 ms, b) 0.15 ms, c) 0.2 ms and d) 0.3 ms after impact of hard missile with v = 250 m/s.

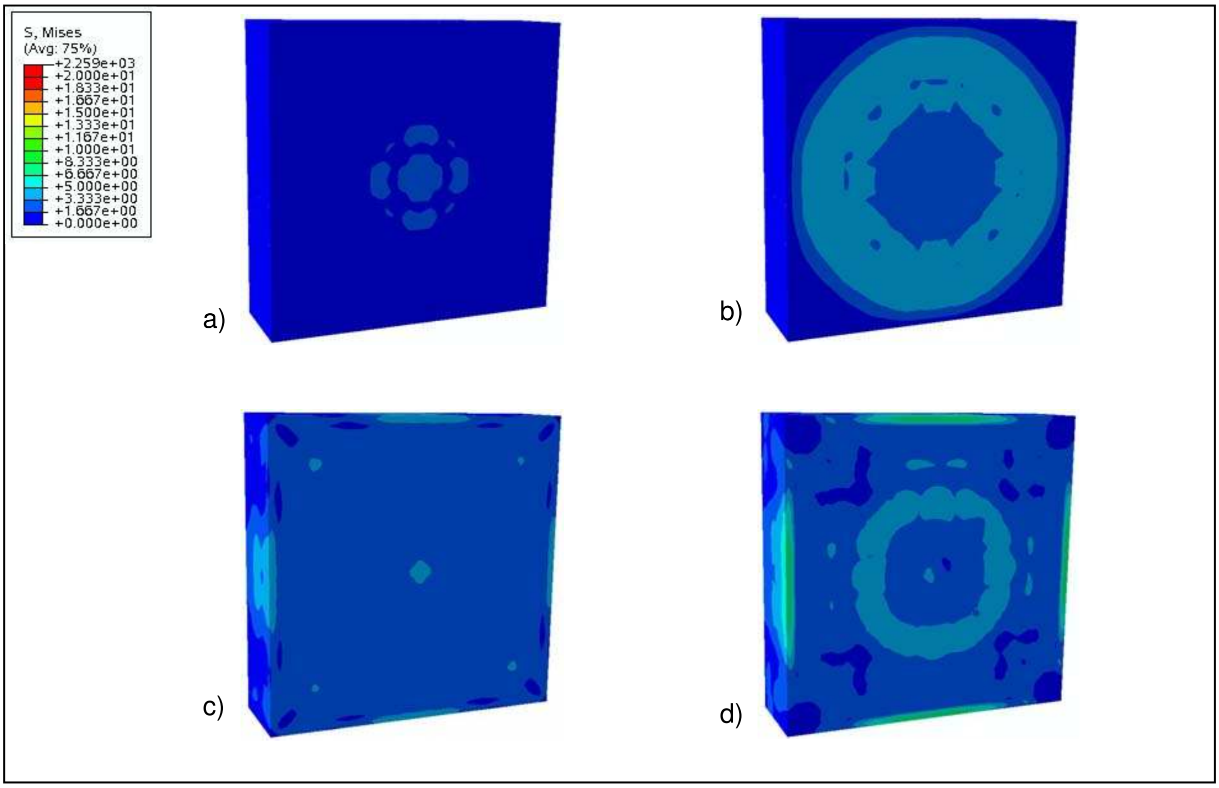

Fig. 19: Van Mises stress distribution on back side of concrete slab a) 0.15 ms, b) 0.2 ms, c) 0.25 ms and d) 0.3 ms after impact of hard missile with v = 250 m/s.

Figures 20 and 21 show the energy balance for the above case in absolute and relative figures respectively. The missile is tremendously slowed down as the curve for the kinetic energy of the missile reveals. The missile loses approximately 95% of its initial kinetic energy and the lost energy is mostly transformed into strain energy of the concrete slab and to smaller extents into viscous dissipation energy, damage dissipation energy and kinetic energy of the concrete slab.

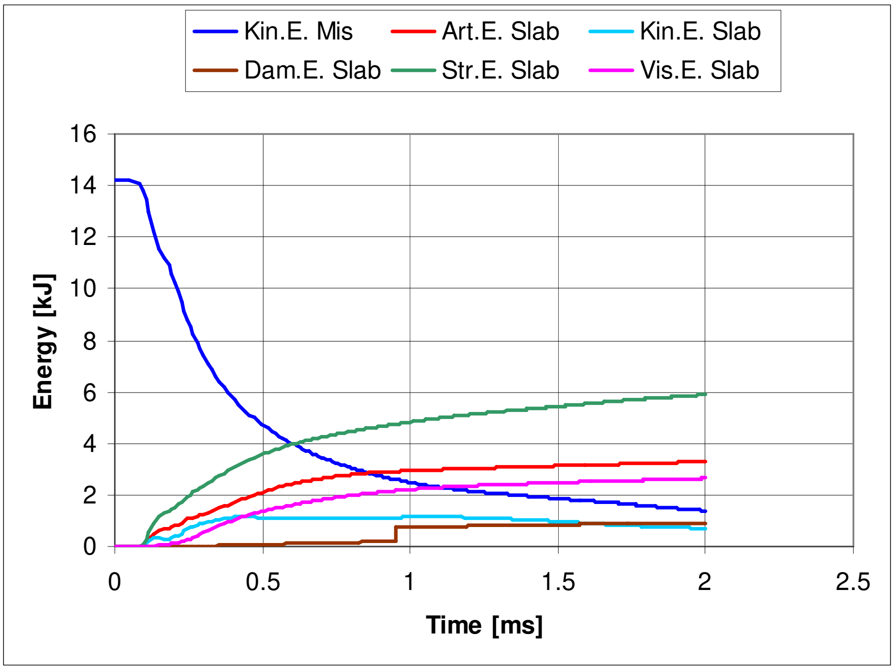

Fig. 20: Energy balance for hard missile with v = 250 m/s.

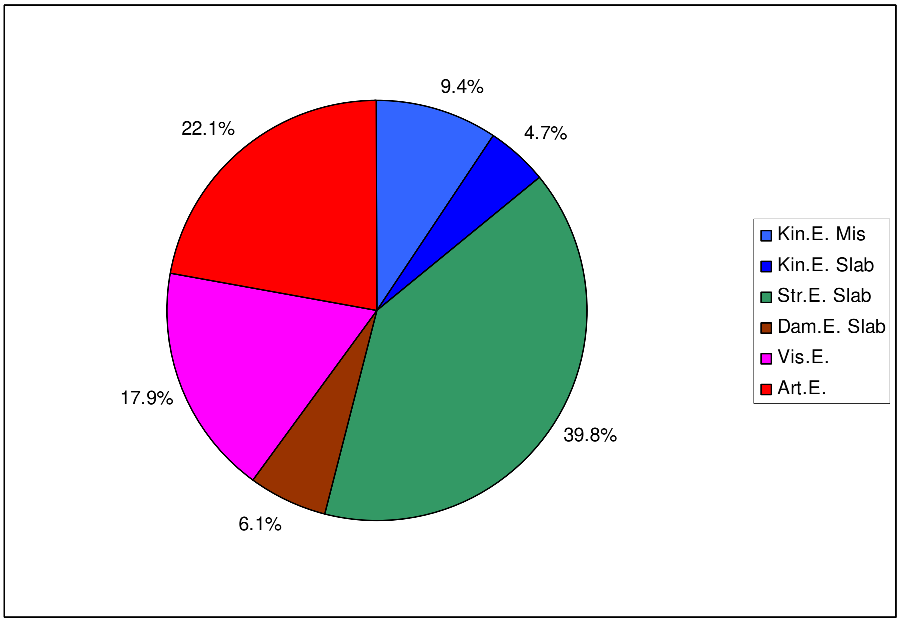

Fig. 21: Transformation of initial missile kinetic energy for hard missile with v = 250 m/s.

Figures 20 and 21 also show that quite an amount of artificial energy builds up. The amount of artificial energy lies in between the viscous dissipation energy and the strain energy of the concrete slab. The reason for its build-up is the adaptive meshing used for all the analyses with the Concrete Damaged Plasticity Model. To avoid excessive distortion of the finite elements of the concrete slab in the impact zone this zone is re-meshed throughout the analyses. Since the hard missile penetrates deeply into the concrete slab during the analyses the finite elements produced by the re-meshing process become smaller. Since smaller finite elements are more vulnerable to distortion and approaching zero volume when they are compressed the FE solver puts additional stiffness on them throughout the analyses leading to the increasing artificial energy. Because the artificial energy lies significantly above certain real physical energies the results of the above case have to be treated with care.

The results of the impact analyses with a hard missile with v=250 m/s in conjunction with the Concrete Damage Plasticity Model of ABAQUS/Explicit reveal the general obstacle of this constitutive model mentioned already in Section 4.3, that it contains no failure criteria. Finite elements with high tension stresses or shear stresses cannot be removed throughout the analysis. This means that perforation of the missile (likely in case of hard missile with high velocities), spalling and scabbing of concrete particles cannot be modelled with the Concrete Damage Plasticity Model. Figure 22 shows one consequence of this. Finite Elements representing concrete, which normally would spall of the concrete slab due to the impact of the missile, stays connected to the concrete slab.

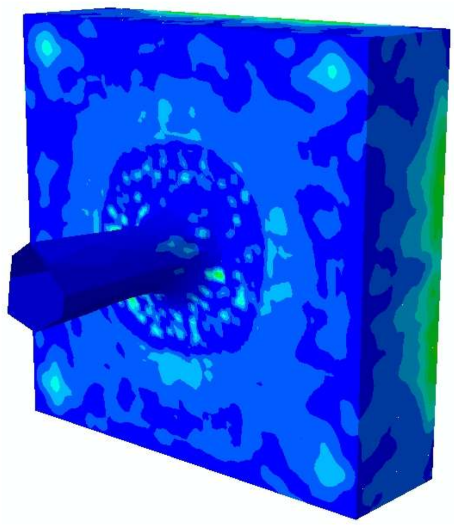

Fig. 22: Deformation of concrete slab due to impact of hard missile with v = 250 m/s after 0.75 ms.

The observed results for the Concrete Damaged Plasticity Model in connection with the hard missile become more apparent at higher missile velocities. Figures 23 and 24 show the van Mises stress distribution in the reinforced concrete slab after the impact of a hard missile with a velocity of 500 m/s, so a relatively high velocity. The reinforced concrete slab is clearly loaded due to the impact of the missile. Strains/stresses are induced inside the concrete slab due to the missile and the strains/stresses propagate through the concrete slab in waves indicating the vibrations of the concrete slab.

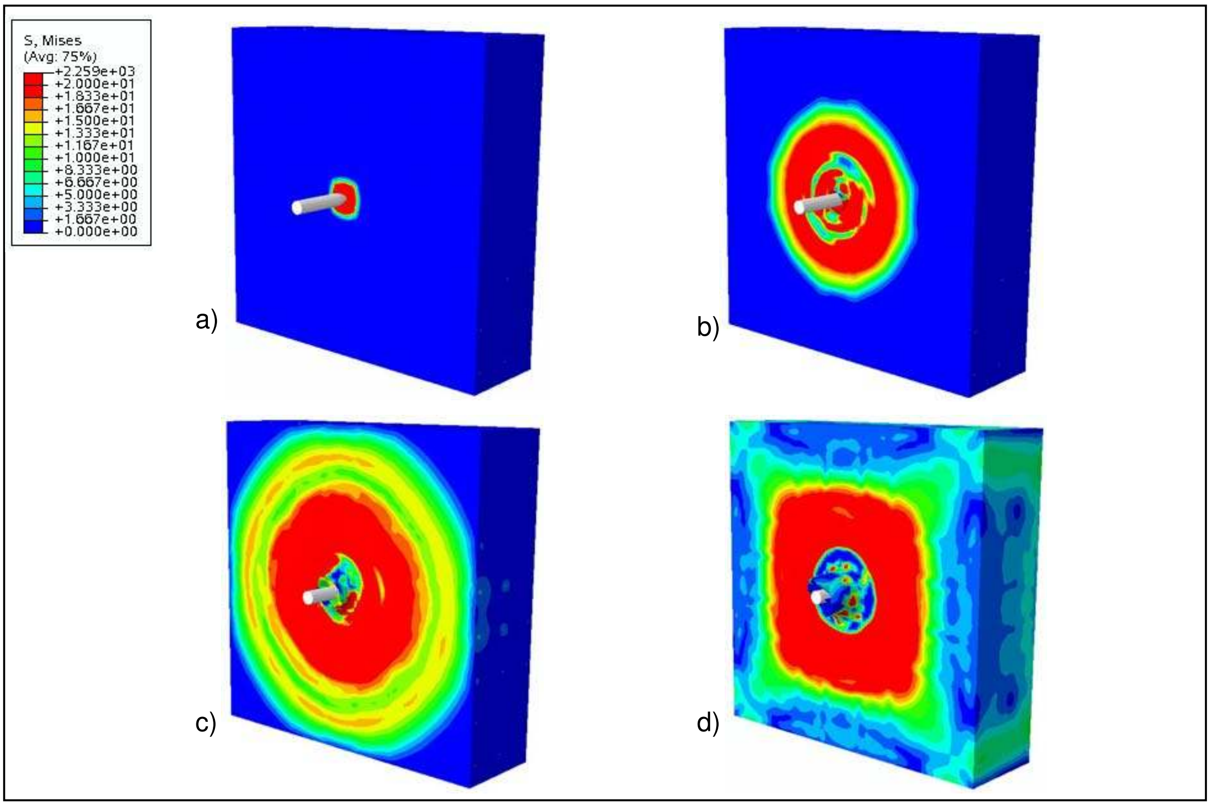

Fig. 23: Van Mises stress distribution on front side of concrete slab a) 0.05 ms, b) 0.1 ms, c) 0.15 ms and d) 0.2 ms after impact of hard missile with v = 500 m/s.

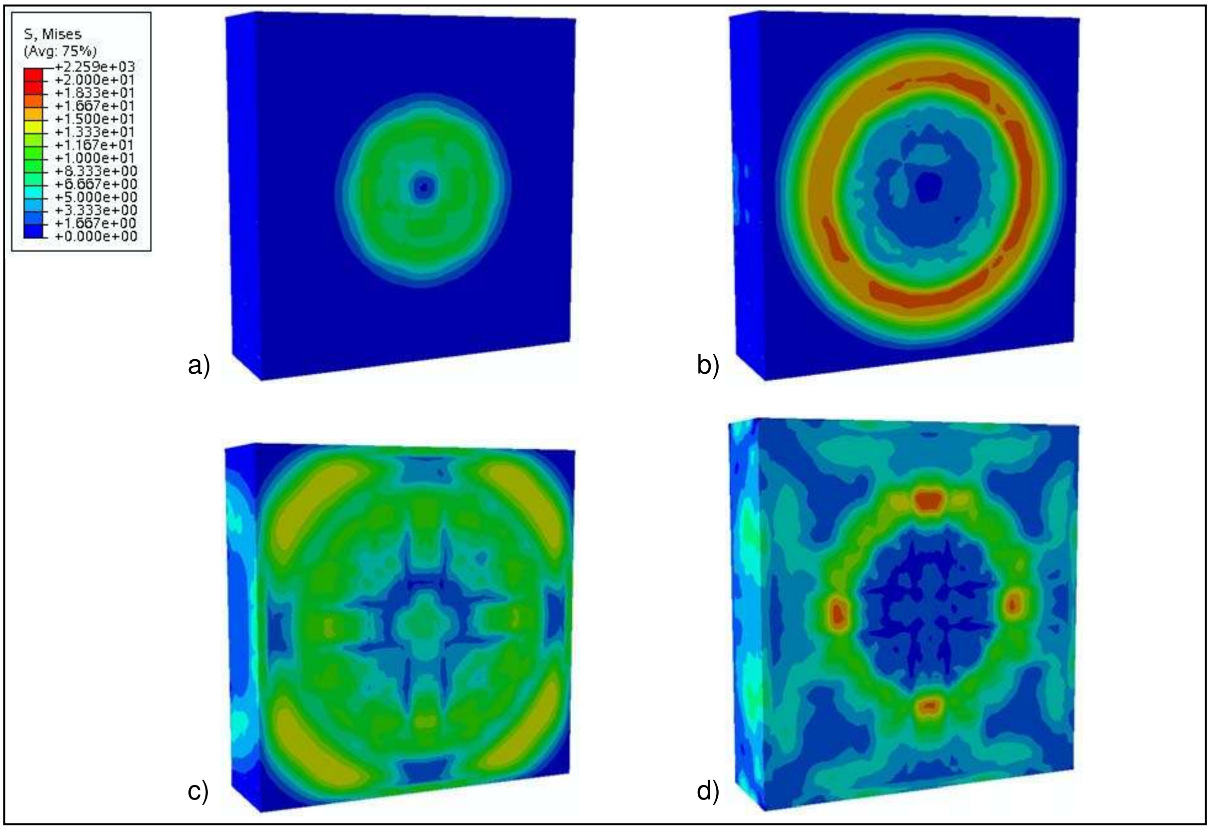

Fig. 24: Van Mises stress distribution on back side of concrete slab a) 0.12 ms, b) 0.15 ms, c) 0.18 ms and d) 0.25 ms after impact of hard missile with v = 500 m/s.

Figure 25 shows the energy balance for the case impact of hard missile with v=500 m/s. Up to a time of 0.67 s the energy balance looks rather similar to the one for the case for impact of hard missile with v=250 m/s. The missile loses nearly all of its initial kinetic energy and the lost energy is mostly transformed into strain energy of the concrete slab and to smaller extents into viscous dissipation energy, kinetic energy and damage dissipation energy of the concrete slab, but also artificial energy. The latter is caused by artificial stiffnesses of the finite elements in the impacted zone of the concrete slab. The artificial stiffnesses reach such high values during the analysis that they reverse the flight direction of the missile. At 0.67 s the missile starts to move in opposite direction its initial flight direction and gains velocity quite considerably. This is visible in the energy balance in Figure 25, where the kinetic energy and all the other energy forms in the system rise again as of 0.67 s, but also in Figure 26, which shows the missile velocity versus time.

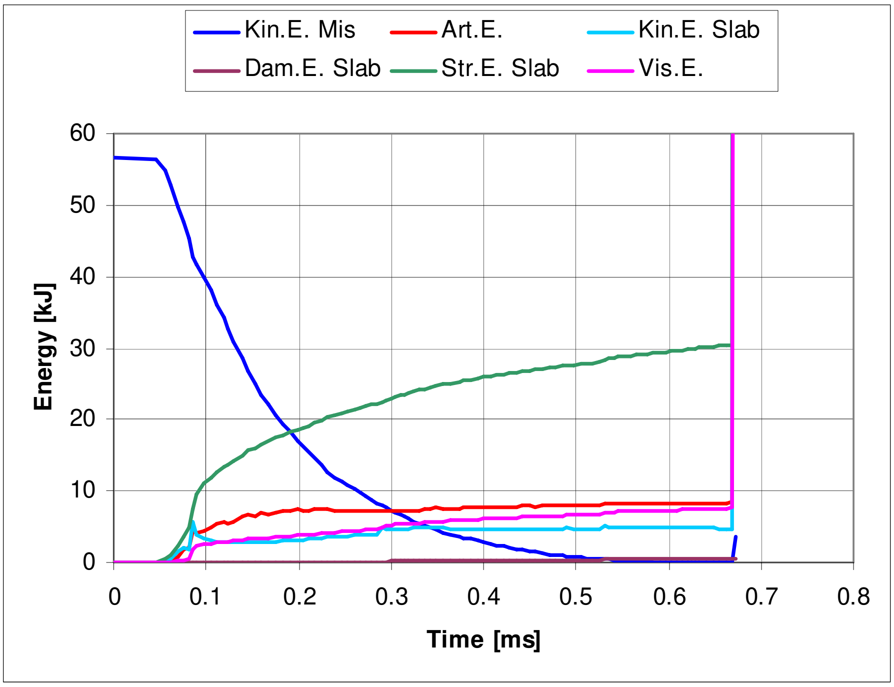

Fig. 25: Energy balance for impact of hard missile with v = 500 m/s.

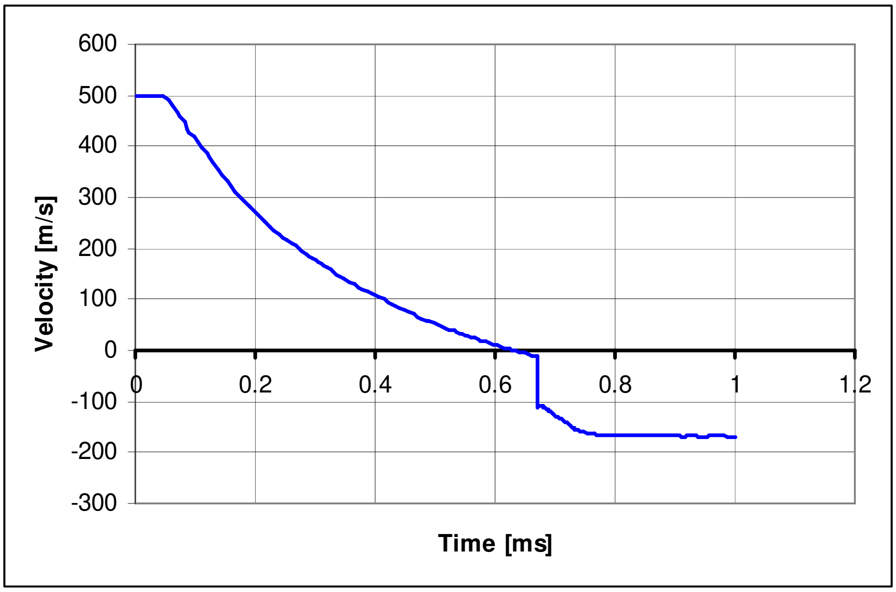

Fig. 26: Missile velocity vs. time for impact of hard missile with v = 500 m/s.

The energy balance for the case hard missile with velocity v=500 m/s emphasises strongly the main weakness of the Concrete Damage Plasticity Model of ABAQUS/Explicit, a missing failure criterion. Instead of removing heavily compressed finite elements they are kept in the FE model throughout the analyses and the FE solver keeps adding artificial stiffness to them. The artificial stiffnesses in the model eventually reach levels so that the flight direction of the missile is completely reversed and that the missile gains kinetic energy, which is in sharp contrast to reality. The problem of missing failure criterion of the Concrete Damage Plasticity Model becomes more apparent for higher missile velocities, so for cases where perforation of hard missiles are more likely.

5.2.2 Results with soft Missile

When a soft missile impacts on a reinforced concrete structure perforation of the missile is less likely straight away than for a hard missile. The penetration depth of a soft missile into a reinforced concrete structure is usually significantly smaller compared to a hard missile of the same velocity. Thus when the impact of a soft missile on a reinforced concrete slab is modelled the numerical implications can be expected to be far less severe compared to impact analyses with a hard missile with an ogive nose. This is what the results of all the analyses with the soft missile for the Concrete Damaged Plasticity Model show.

Figures 27 and 28 show the van Mises stress distribution inside the reinforced concrete slab for various moments in time after the impact of a soft missile with a velocity of 250 m/s. Also with the soft missile the concrete slab is clearly loaded due to the impact of the missile, i.e. strains/stresses are induced inside the concrete slab and they propagate in waves through the concrete slab.

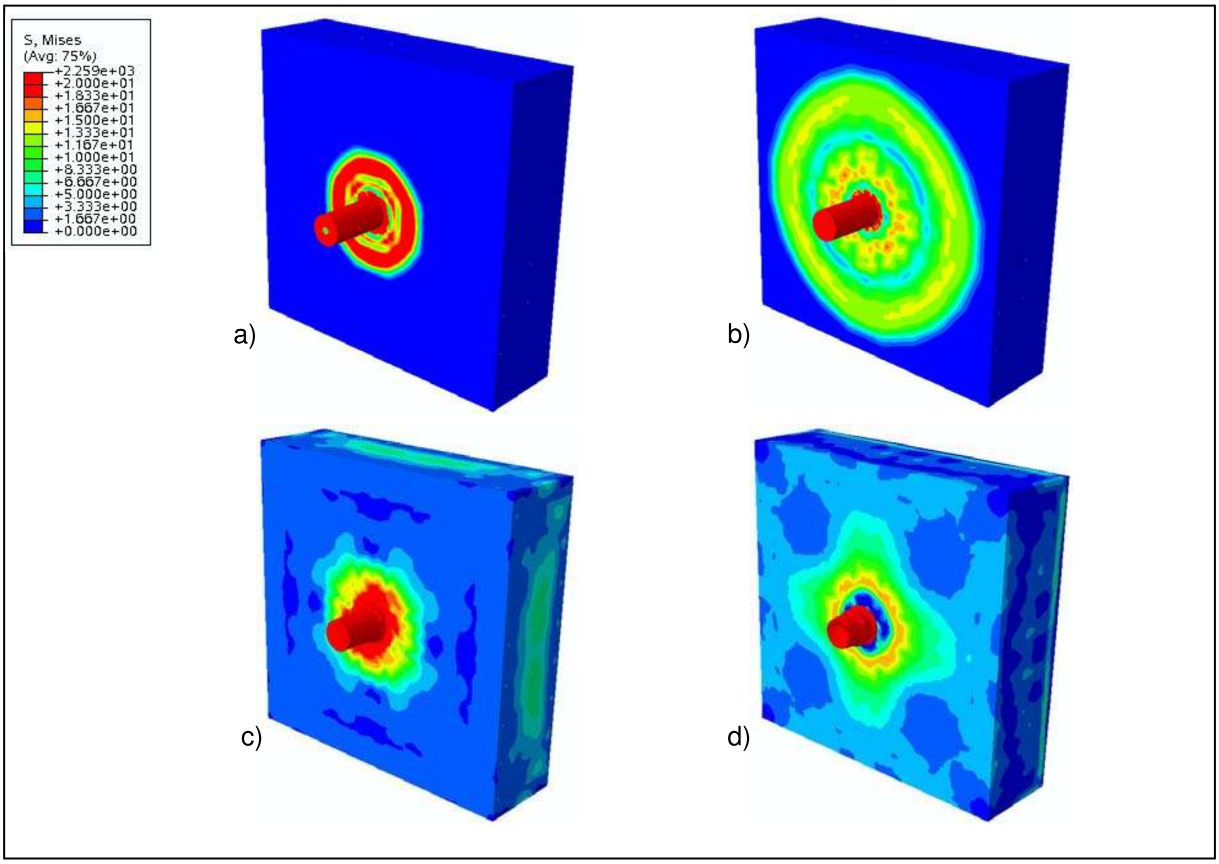

Fig. 27: Van Mises stress distribution on front side of concrete slab a) 0.1 ms, b) 0.15 ms, c) 0.25 ms and d) 2 ms after impact of soft missile with v = 250 m/s.

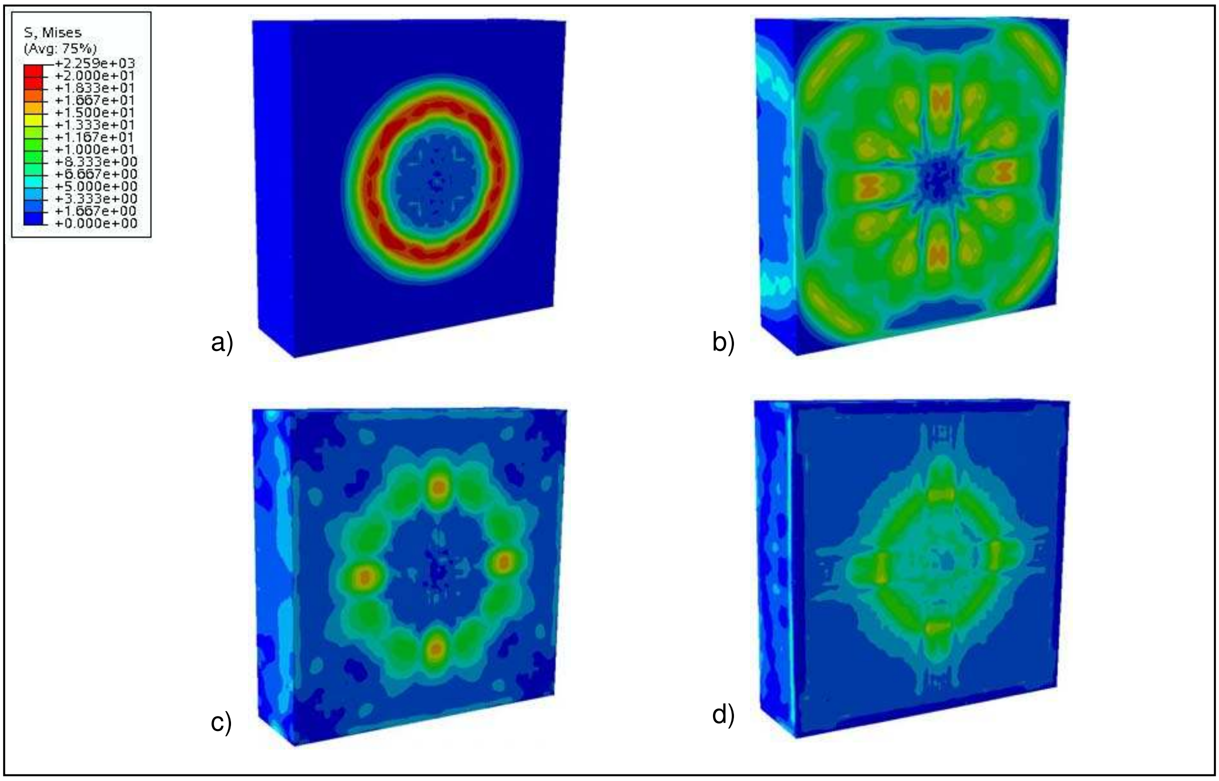

Fig. 28: Van Mises stress distribution on front side of concrete slab a) 0.15 ms, b) 0.2 ms, c) 0.3 ms and d) 2 ms after impact of soft missile with v = 250 m/s.

Since the penetration depth for the soft missile is far smaller compared to the hard missile the

FE solver puts basically no artificial stiffness on the finite elements of the concrete slab around the impacted zone. The effect is that the amount of artificial energy in the system stays limited as the energy balances in Figures 29 and 30 show. Interesting is that the soft missile loses all its kinetic energy relatively quickly and that most of it is transformed into strain energy of the missile and to smaller extents into strain energy of the concrete slab and viscous dissipation energy. This can be expected since the soft missile is much more flexible and thus deformable than the reinforced concrete slab. The kinetic energy of the reinforced concrete slab is considerably smaller than the other physical energies, but shows a small peak directly after the impact of the soft missile. This is realistic since the vibration amplitudes of an impacted structure are always the highest immediately after the impact of the missile. Generally the energy balance for the analysis of the impact of a soft missile with a velocity of 250 m/s in connection with the Concrete Damaged Plasticity Model is reasonable and sound.

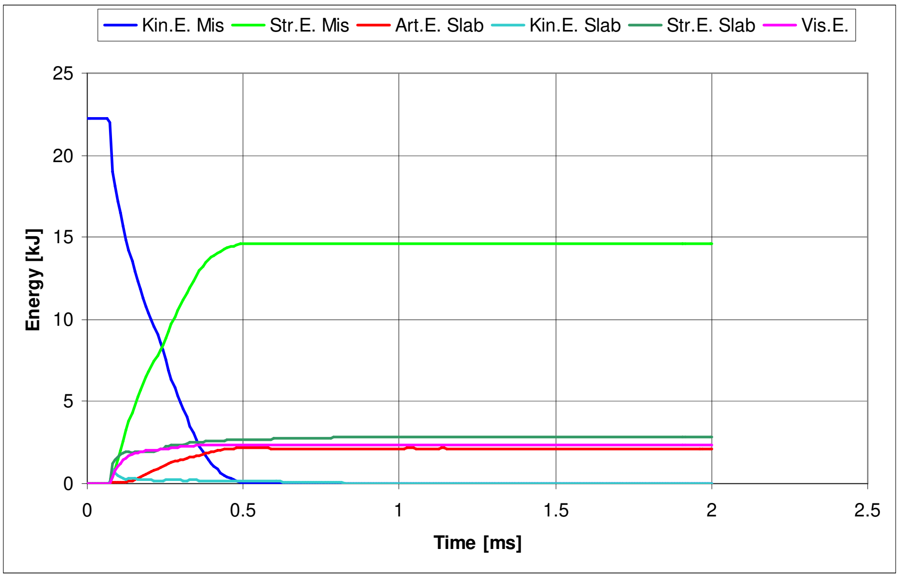

Fig. 29: Energy balance for impact of soft missile with v = 250 m/s.

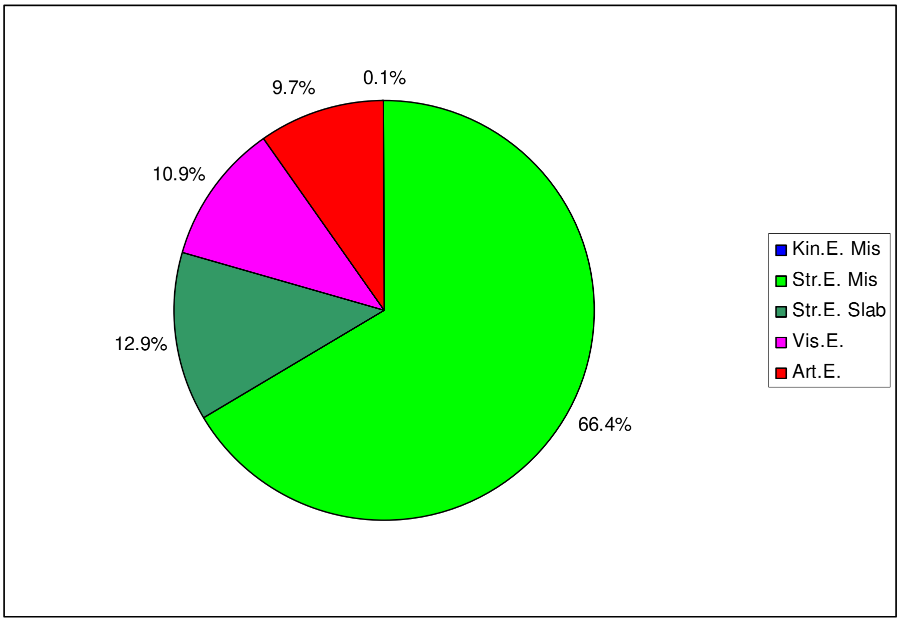

Fig. 30: Transformation of initial missile kinetic energy for soft missile with v = 250 m/s.

The observed results for the soft missile with an initial velocity of 250 m/s can also be observed for other missile velocities. Figures 31 and 32 show the van Mises stress distribution inside the reinforced concrete slab for various moments in time after the impact of a slow soft missile with a velocity of 75 m/s. Also here the impact of the soft missile clearly induces strains/stresses in the concrete slab and they propagate in waves through the concrete slab. The energy balance in Figure 33 shows once again that the soft missile loses all its kinetic energy relatively quickly and most of it is transformed into strain energy of the missile and to smaller extents into strain energy of the concrete slab and viscous dissipation energy (see Figure 34). The kinetic energy of the reinforced concrete slab is low and again has a small peak immediately after the impact of the soft missile. The artificial energy is significantly lower than for the case with initial missile velocity of 250 m/s.

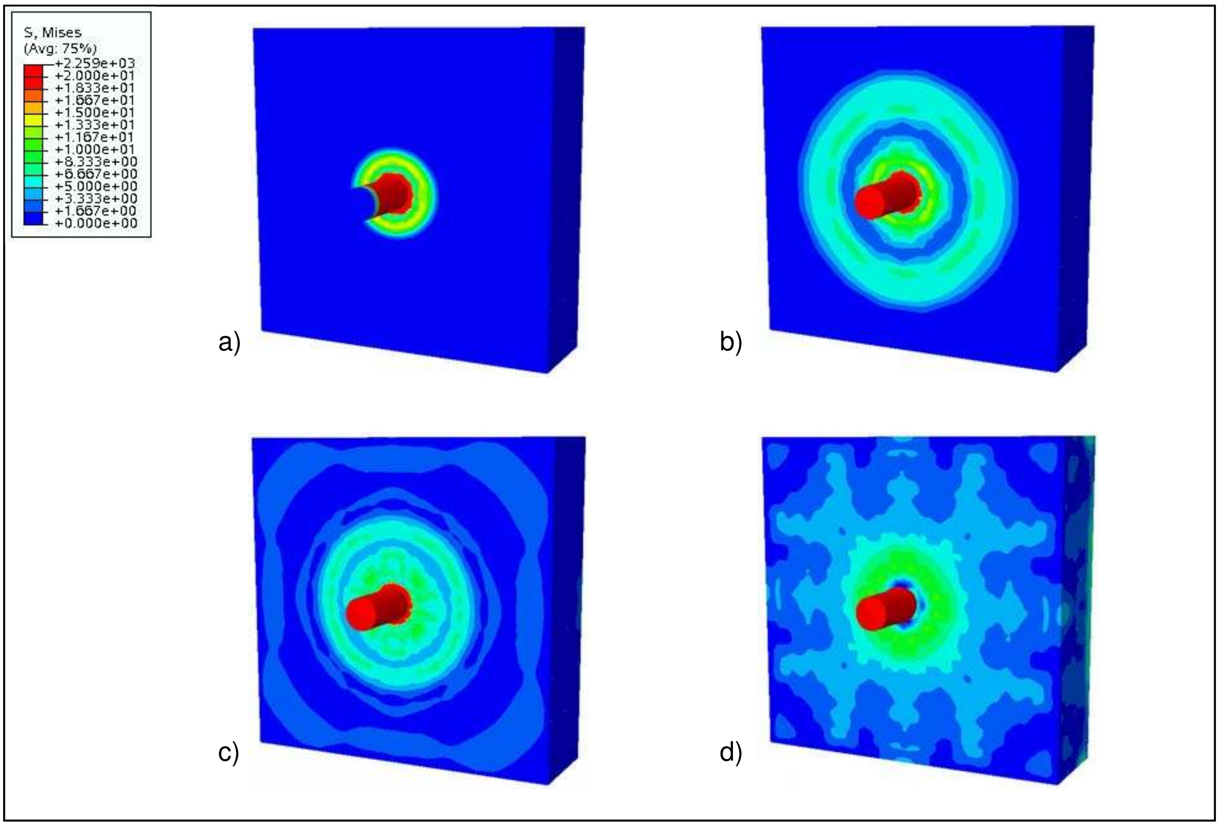

Fig. 31: Van Mises stress distribution on front side of concrete slab a) 0.25 ms, b) 0.3 ms, c) 0.35 ms and d) 1 ms after impact of soft missile with v = 75 m/s.

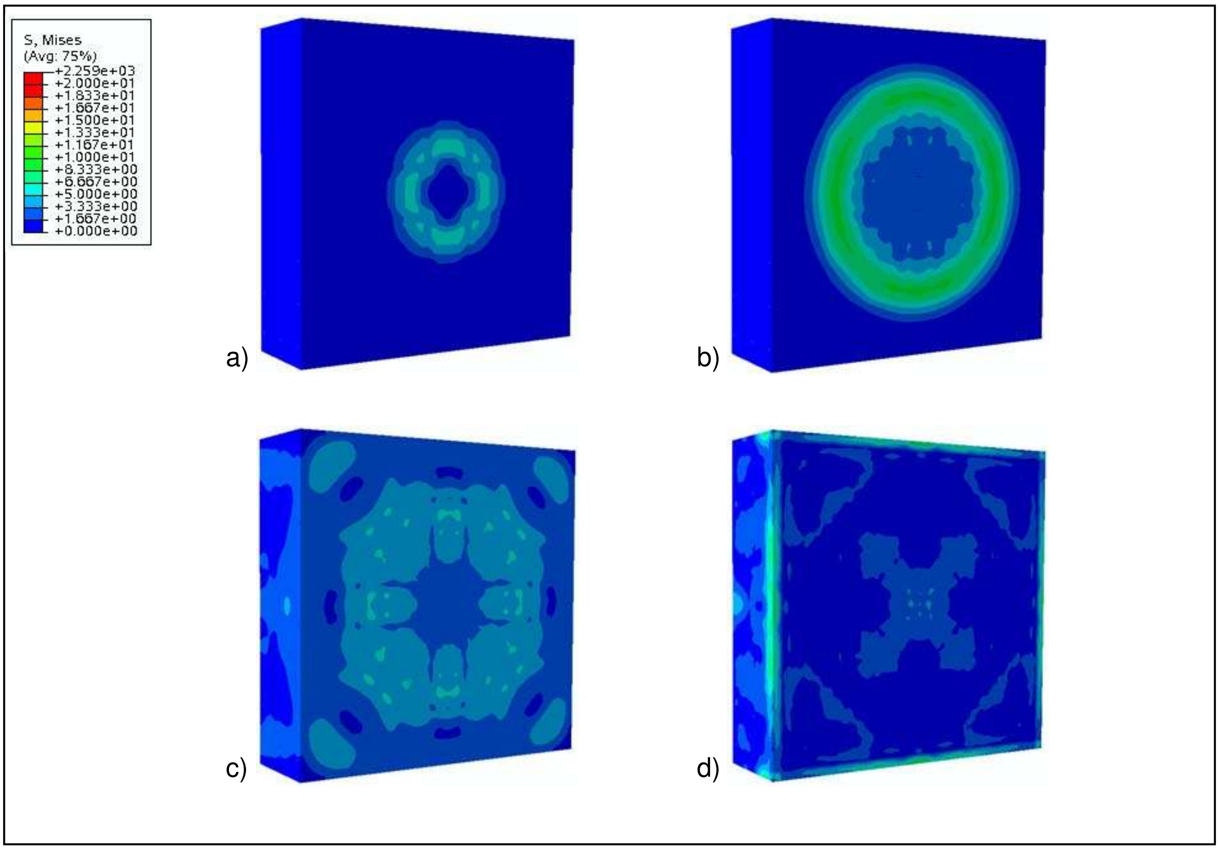

Fig. 32: Van Mises stress distribution on back side of concrete slab a) 0.3 ms, b) 0.325 ms, c) 0.375 ms and d) 1 ms after impact of soft missile with v = 75 m/s.

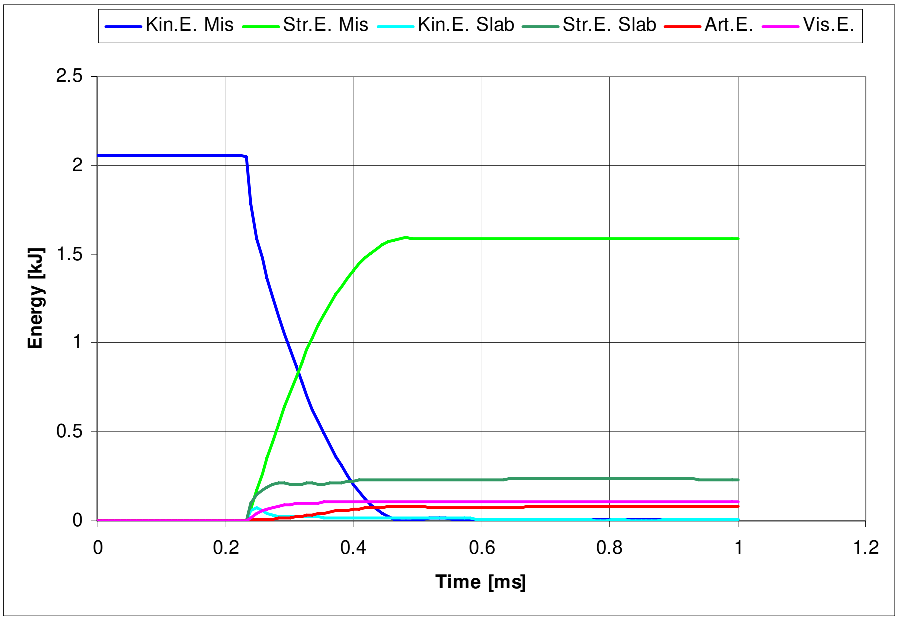

Fig. 33: Energy balance for impact of soft missile with v = 75 m/s.

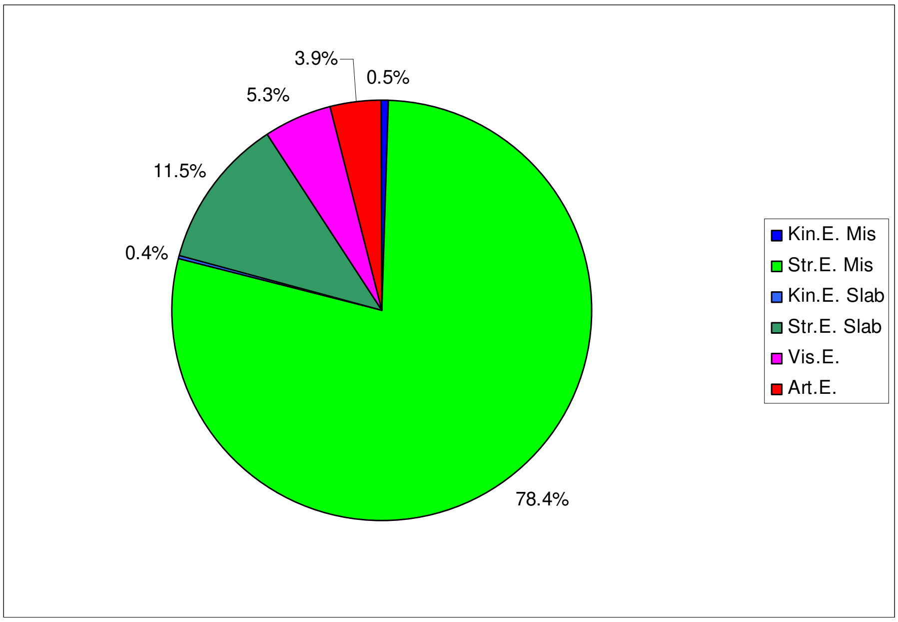

Fig. 34: Transformation of initial missile kinetic energy for soft missile with v = 75 m/s.

Figures 35 and 36 show the van Mises stress distribution inside the reinforced concrete slab for various moments in time for the impact of a fast soft missile with a velocity of 500 m/s. Also here the impact of the soft missile clearly loads the reinforced concrete slab. Strains/stresses are clearly visible in the concrete slab and they propagate in waves through the concrete slab. The Figures 37 and 38 show the energy balances in absolute and relative figures respectively. As before the soft missile loses all its kinetic energy relatively quickly and most of it is transformed into strain energy of the missile and to smaller extents into viscous dissipation energy and strain energy of the concrete slab. The kinetic energy of the reinforced concrete slab is low and again has a small peak immediately after the impact of the soft missile. The artificial energy lies in the range of the kinetic energy of the concrete slab and is low, lower than for the previous two missile velocities. The energy balance for the impact of a soft missile with a velocity of 500 m/s in connection with the Concrete Damaged Plasticity Model is reasonable and sound.

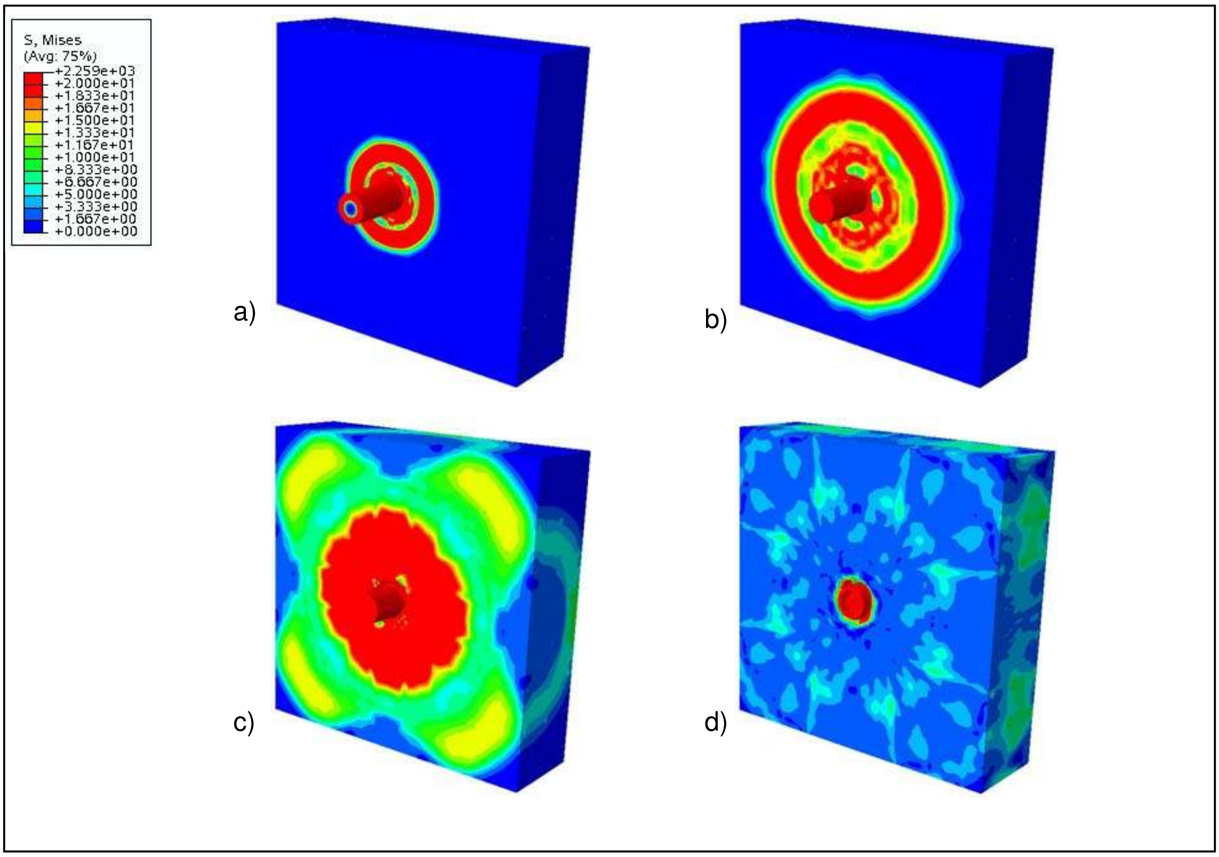

Fig. 35: Van Mises stress distribution on front side of concrete slab a) 0.06 ms, b) 0.1 ms, c) 0.15 ms and d) 0.4 ms after impact of soft missile with v = 500 m/s.

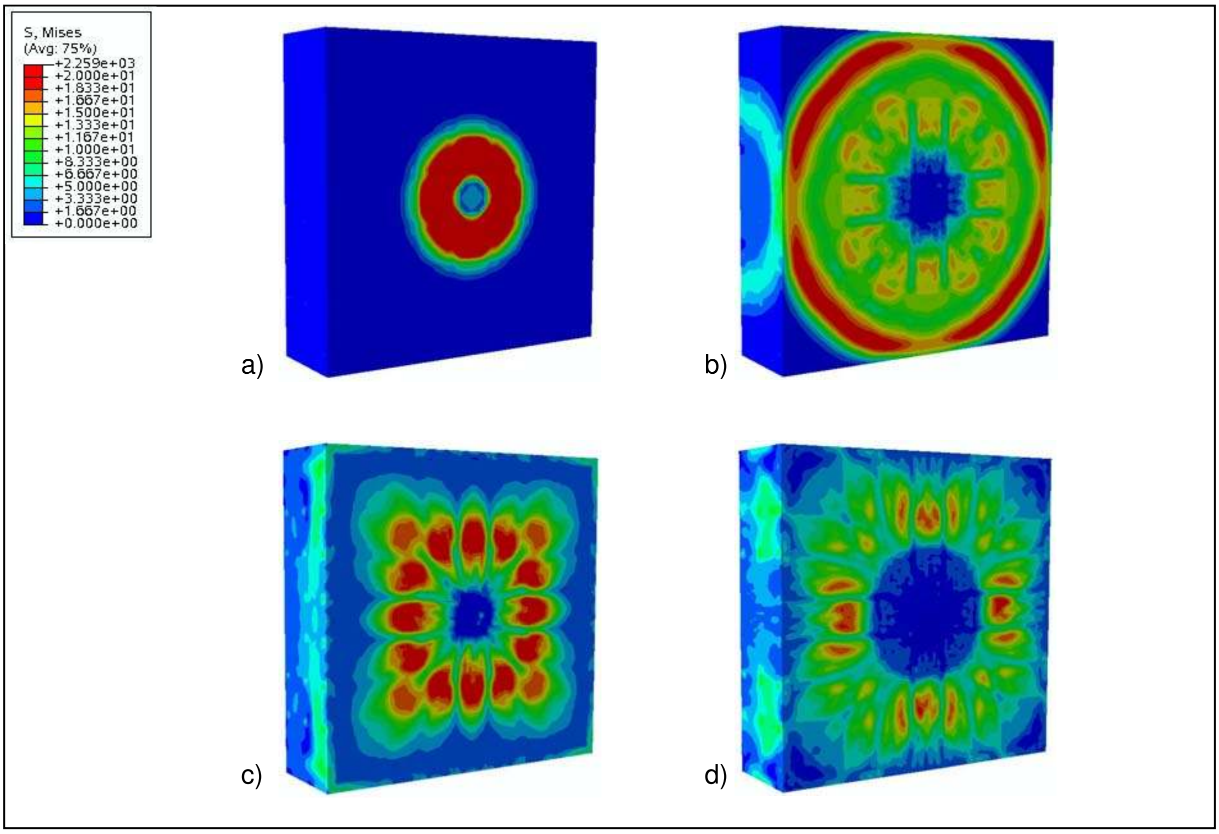

Fig. 36: Van Mises stress distribution on back side of concrete slab a) 0.1 ms, b) 0.15 ms, c) 0.2 ms and d) 0.4 ms after impact of soft missile with v = 500 m/s.

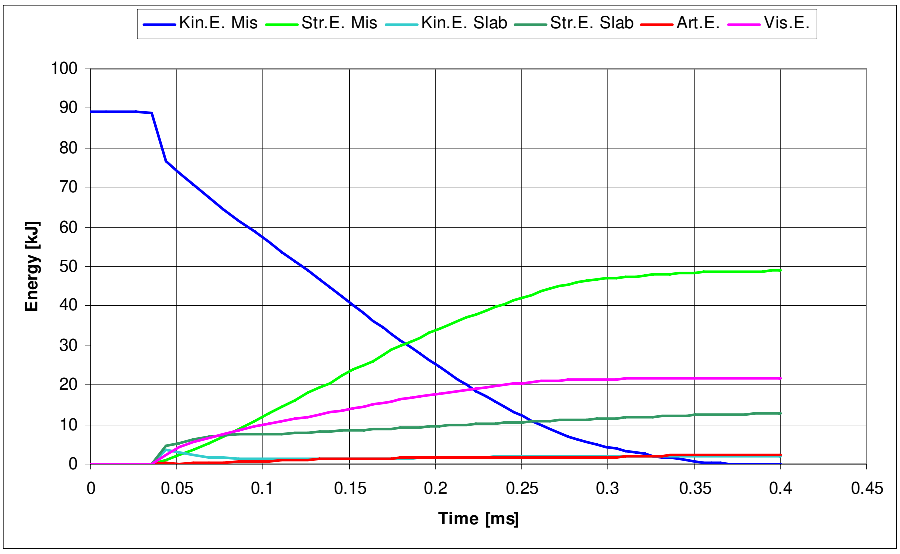

Fig. 37: Energy balance for impact of soft missile with v = 500 m/s.

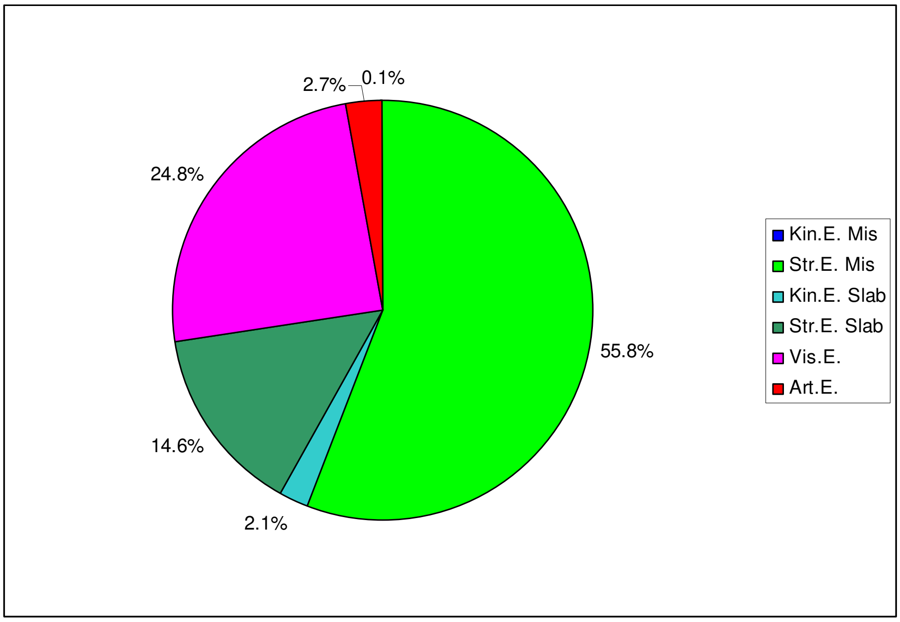

Fig. 38: Transformation of initial missile kinetic energy for soft missile with v = 500 m/s.

When the Figures 27d), 31d) and 35d) are compared with each other it is immediately visible that the missile deforms stronger with increasing missile velocity. For an initial missile velocity of v=500 m/s the missile is completely pushed together. As observed before most of the initial kinetic energy of the missile is transformed into strain energy of the missile. Since the amount of energy in the system rises with higher initial missile velocities in absolute terms the missile eventually deforms more strongly at higher initial missile velocities.

Remarkable is also how the proportions of physical energies into which the initial kinetic energy of the missile is transformed change with initial missile velocity. Figure 39 shows these proportions versus the initial missile velocity. For rising initial missile velocities the proportion of the strain energy of the missile as of the initial missile kinetic energy reduces, where as the proportions for the strain energy of concrete slab and especially for the viscous dissipation energy rise. With rising initial missile velocities the effect of viscous damping becomes more significant. Thus a higher proportion of the overall energy in the system is allocated to viscous damping at the cost of strain energy of the missile.

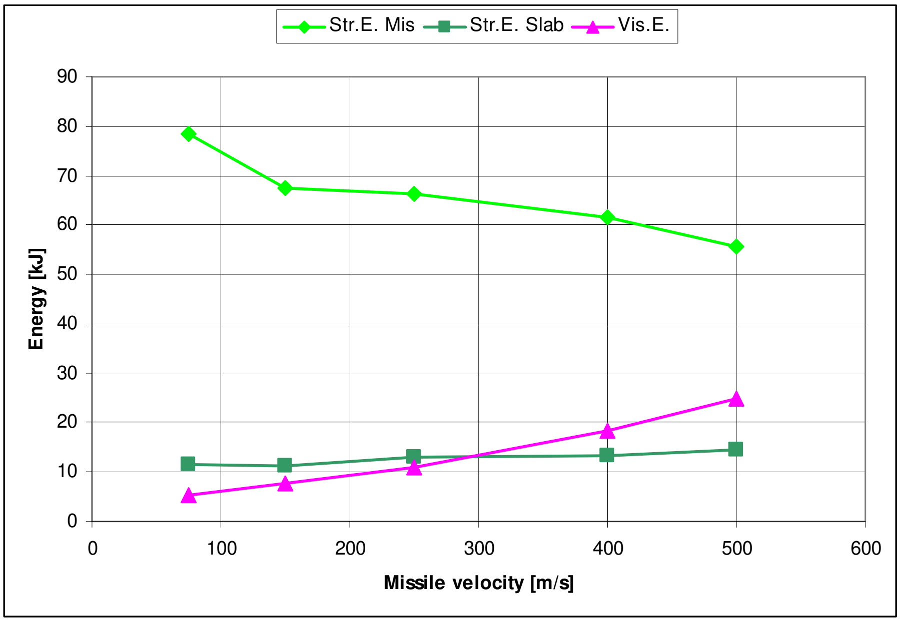

Fig. 39: Proportions of physical energies into which initial kinetic energy of missile is transformed to vs. missile velocity.

Figure 40 shows the buckling of the centre of the backside of the reinforced concrete slab versus the initial missile velocity. With rising missile velocity the concrete slab buckles more strongly on its back side, which resembles reality.

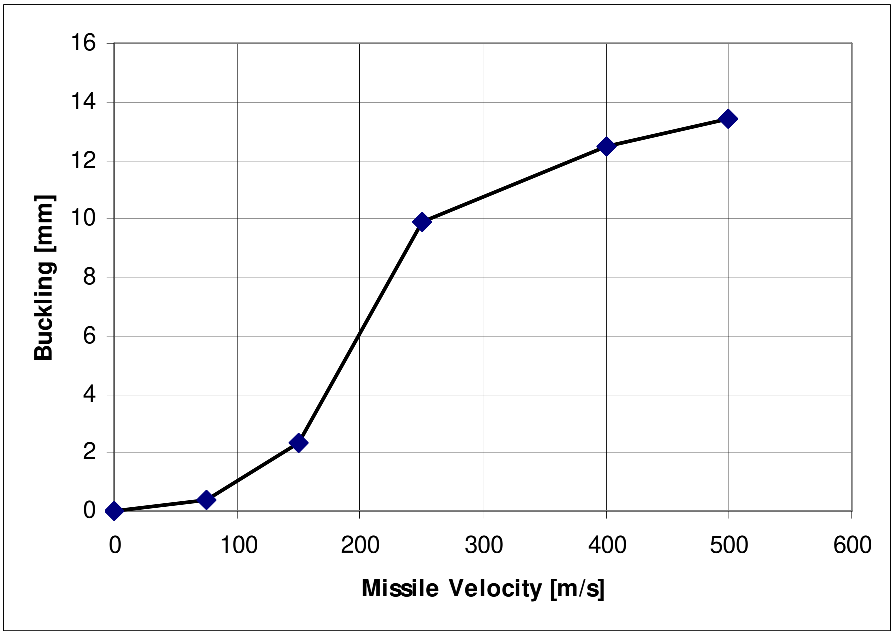

Fig. 40: Buckling on back side of concrete slab vs. missile velocity.

In conclusion the results for the Concrete Damaged Plasticity Model with the soft missile are physically realistic and sound.

6 Summary and Outlook

Numerical missile impact analyses on a reinforced concrete slab were performed with the FE solver ABAQUS/Explicit. The FE model of the impacted reinforced concrete slab resembles are structure used in the missile impact tests by Hanchak et al. Traditional Lagrangian formulations for both the missiles and reinforced concrete slabs were used, i.e. the missiles and the reinforced concrete slab where modelled with solid 3D meshes (HEX elements (C3D8/C3D8R) and shell elements (S3R and S4R). Two different build-in constitutive models for concrete in ABAQUS/Explicit, the Brittle Cracking Model and the Concrete Damaged Plasticity Model, are used and their suitability and limitations for missile impact analyses were explored. A hard and a soft missile were used for both constitutive models and sensitivity studies related to the initial missile velocity were performed.

The results show that the Concrete Cracking Model of ABAQUS/Explicit does not seem to be a suitable constitutive model to model missile impacts on reinforced concrete slabs when solid 3D meshes are used. The constitutive model in principle allows the setting of a failure strain (brittle failure strain) as of which elements are removed from the FE model when their strain has reached that value. It turned out that the brittle failure strain has to be set to extremely low values in order to avoid numerical difficulties and achieve completion of analyses. Quite a number of elements are heavily distorted and there is no evidence for any loading of the reinforced concrete slab due to the impact of the missiles in the form of strains/stresses propagating through the reinforced concrete slab. The hard missile perforates through the reinforced concrete slab while keeping most of its initial kinetic energy. The soft missile loses all its initial kinetic energy, but also penetrates quite deeply into the reinforced concrete slab, which does not reflect the outcome of the known missile tests.

With the Concrete Damaged Plasticity Model the reinforced concrete slab clearly shows loading due to the impact of the missiles. Strains/stresses are induced in the concrete slab and they propagate in waves through the concrete slab. Since the Concrete Damaged Plasticity Model does not contain any failure criterion large amounts of artificial energies can build-up during the analyses as a result of adding artificial stiffnesses to finite elements by the FE solver in order to avoid excessive compression and distortion of elements to zero volume. This is indeed a problem for the hard missile especially with high initial velocities. For cases, where a deep penetration of the missile into the reinforced concrete slab is unlikely straight from the beginning, i.e. a soft missile, the Concrete Damaged Plasticity Model of ABAQUS/Explicit leads to reasonable and sound results in terms of strains/stresses of the reinforced concrete slab, overall energy balances and overall deformation of the concrete slab. One obstacle of the Concrete Damage Plasticity Model remains: Due to a missing failure criterion, perforation of the missile, spalling and scabbing of concrete cannot be modelled with that constitutive model.

The results of the performed FE analyses showed clearly the numerical problems and limitations of the Lagrangian formulation in numerical modelling of missile impacts on concrete structures. To overcome these limitations different methodologies are needed, which either use hydrodynamic models, i.e. Smoothed Particle Hydrodynamics (SPH), or incorporate Eulerian formulation, i.e. Coupled Eulerian Lagrangian (CEL). Eventually both methodologies have to be used in combination with different constitutive models, e.g. Equation of State (EOS) Models.

7 References

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APPENDIX: ABAQUS Input Files

ABAQUS Input File with Brittle Cracking Model

```
**
** ABAQUS Input File with Brittle Cracking Model
**
**  Template:  ABAQUS/EXPLICIT
**
**----------------------
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**----------------------
**
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        2,  101.66666666667,  19.0625        ,  31.785714285714

        ...
**
**-------------------------
** Element Definitions
**-------------------------
**
*ELEMENT, TYPE=T3D2, ELSET=Rebars
   260917,    211713,    210968
   260918,    211647,    211713

        ...

*ELEMENT, TYPE=S3, ELSET=SH_soft_missile
   265525,      3204,      6708,      7473
   265530,      3204,      7473,      7468

      ...

 *ELEMENT, TYPE=S4, ELSET=SH_soft_missile
   265526,      6708,      6419,      7472,      7473
   265527,      6419,      7475,      7471,      7472

      ...

*ELEMENT, TYPE=C3D8R, ELSET=HEX_Concrete
        1,    140931,    142544,    142541,    140919,    142555,    142597,    142554,
   142545
        2,    142530,    142531,    142544,    140931,    142596,    142472,    142597,
   142555

      ...

**
**--------------------------
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**--------------------------
**
*NSET, NSET=...
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**-------------------------------
** Element Set Definitions
**-------------------------------
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*ELSET, ELSET=...
     ...

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**-----------------------------------
** Contact Surface Definitions
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,
HEX_Concrete, INTERIOR

**
**------------------------------------------
** Shell & Solid Section Definitions
**------------------------------------------
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 3.0
*SOLID SECTION, ELSET=HEX_Concrete, MATERIAL=Concrete
*SOLID SECTION, ELSET=Rebars, MATERIAL=Rebar_steel
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Rebars

**
**---------------------------
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 1.94393      ,0.0001
 1.30305      ,0.0002
 0.873463     ,0.0003
 0.5855       ,0.0004
 0.392472     ,0.0005
 0.263082     ,0.0006
 0.176349     ,0.0007
 0.11821      ,0.0008
 0.0792388    ,0.0009
 0.0531154    ,0.001
*BRITTLE SHEAR
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 0.125, 0.003
*BRITTLE FAILURE, CRACKS=1
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**
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*PLASTIC
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 380.0     ,1.0
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**----------------------------------------------------------------------
* Definition of initial missile velocity & boundary conditions
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*BOUNDARY
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* Load Step Definition
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*DYNAMIC, EXPLICIT
 ,2.E-3
*CONTACT
*CONTACT INCLUSIONS
 AllSurf
**
**---------------------
** Output Settings
**---------------------
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*OUTPUT, HISTORY, OP=NEW, FREQUENCY=40
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 ALLIE, ALLSE, ALLPD, ALLCD, ALLAE, ALLDMD, ALLDC, ALLFC, ALLKE, ALLVD
*ENERGY OUTPUT, PER ELEMENT SET, ELSET=Rebars
 ALLIE, ALLSE, ALLPD, ALLCD, ALLAE, ALLDMD, ALLDC, ALLFC, ALLKE, ALLVD
*ENERGY OUTPUT, PER ELEMENT SET, ELSET=Rebars2
 ALLIE, ALLSE, ALLPD, ALLCD, ALLAE, ALLDMD, ALLDC, ALLFC, ALLKE, ALLVD
**
*END STEP
```

ABAQUS Input File with Concrete Damage Plasticity Model

```
**
** ABAQUS Input File with Concrete Damage Plasticity Model
**
**   Template: ABAQUS/EXPLICIT
**
**----------------------
** Node Definitions
**----------------------
**
*NODE
       1, 298.64583333333, 19.0625       , 139.85714285714
       2, 101.66666666667, 19.0625       , 31.785714285714

       ...
**
**-------------------------
** Element Definitions
**-------------------------
**
*ELEMENT, TYPE=T3D2, ELSET=Rebars
   260917,   211713,   210968
   260918,   211647,   211713

       ...

*ELEMENT, TYPE=S3, ELSET=SH_soft_missile
   265525,     3204,     6708,     7473
   265530,     3204,     7473,     7468

      ...

 *ELEMENT, TYPE=S4, ELSET=SH_soft_missile
   265526,     6708,     6419,     7472,     7473
   265527,     6419,     7475,     7471,     7472

      ...

*ELEMENT, TYPE=C3D8R, ELSET=HEX_Concrete
       1,   140931,   142544,   142541,   140919,   142555,   142597,   142554,
   142545
       2,   142530,   142531,   142544,   140931,   142596,   142472,   142597,
   142555

      ...

**
**-------------------------
** Node Set Definitions
**---------------------------
**
*NSET, NSET=...
     ...

**
**-----------------------------
** Element Set Definitions
**-----------------------------
```

```
**
*ELSET, ELSET=...
    ...

**
**------------------------------------
** Contact Surface Definitions
**------------------------------------
**
*SURFACE, NAME=AllSurf
,
HEX_Concrete, INTERIOR

**
**------------------------------------------
** Shell & Solid Section Definitions
**------------------------------------------
**
*SHELL SECTION, ELSET=SH_soft_missile, MATERIAL=Rebar_steel
 3.0
*SOLID SECTION, ELSET=HEX_Concrete, MATERIAL=Concrete
*SOLID SECTION, ELSET=Rebars, MATERIAL=Rebar_steel
 25.5
*EMBEDDED ELEMENT, HOST ELSET = HEX_Concrete
Rebars

**
**----------------------------
** Materials Definitions
**----------------------------
**
*MATERIAL, NAME=Concret
**
*DENSITY
 2.5650E-09
*ELASTIC, TYPE=ISOTROPIC
 20800.0, 0.175
*CONCRETE DAMAGED PLASTICITY
 36.31
*CONCRETE COMPRESSION HARDENING
 13.0, 0.000
 24.1, 0.001
*CONCRETE TENSION STIFFENING, TYPE=DISPLACEMENT
 2.9          ,0.0
 1.94393      ,0.066185
 1.30305      ,0.12286
 0.873463     ,0.173427
 0.5855       ,0.22019
 0.392472     ,0.264718
 0.263082     ,0.308088
 0.176349     ,0.35105
 0.11821      ,0.394138
 0.0792388    ,0.437744
 0.0531154    ,0.482165
*CONCRETE TENSION DAMAGE, TYPE=DISPLACEMENT
 0.0          ,0.0
 0.381217     ,0.066185
 0.617107     ,0.12286
 0.763072     ,0.173427
 0.853393     ,0.22019
```

```
 0.909282    ,0.264718
 0.943865    ,0.308088
 0.965265    ,0.35105
 0.978506    ,0.394138
 0.9867      ,0.437744
 0.99177     ,0.482165
**
*MATERIAL, NAME=Rebar_steel
**
*DENSITY
 7.85E-09
*ELASTIC, TYPE=ISOTROPIC
 199000    ,0.3
*PLASTIC
 220.0     ,0.0
 320.0     ,0.25
 370.0     ,0.5
 380.0     ,1.0
**
**----------------------------------------------------------------------
* Definition of initial missile velocity & boundary conditions
**----------------------------------------------------------------------
**
*INITIAL CONDITIONS, TYPE = VELOCITY
 Nsoft,3,-2.5E5
*BOUNDARY
 NBC, 3, ,
**
**--------------------------
* Load Step Definition
**--------------------------
**
*STEP
*DYNAMIC,EXPLICIT
 ,2.E-3
*CONTACT
*CONTACT INCLUSIONS
 AllSurf
*ADAPTIVE MESH, ELSET=Eadap_Concrete
**
**---------------------
** Output Settings
**---------------------
**
*OUTPUT, FIELD, OP=NEW, NUMBER INTERVAL=40, TIMEMARKS=YES
*ELEMENT OUTPUT
 S, PEEQ, LE, PE
*NODE OUTPUT
 U,
*OUTPUT, HISTORY, OP=NEW, FREQUENCY=40
*NODE OUTPUT, NSET=Nsoft_front
 U, V, A
*NODE OUTPUT, NSET=Nsoft_back
 U, V, A
*NODE OUTPUT, NSET=Nbend
 U
*ENERGY OUTPUT, PER ELEMENT SET, ELSET=SH_soft_missile
 ALLIE, ALLSE, ALLPD, ALLCD, ALLAE, ALLDMD, ALLDC, ALLFC, ALLKE, ALLVD
*ENERGY OUTPUT, PER ELEMENT SET, ELSET=HEX_Concrete
 ALLIE, ALLSE, ALLPD, ALLCD, ALLAE, ALLDMD, ALLDC, ALLFC, ALLKE, ALLVD
```

```
*ENERGY OUTPUT, PER ELEMENT SET, ELSET=Rebars
 ALLIE, ALLSE, ALLPD, ALLCD, ALLAE, ALLDMD, ALLDC, ALLFC, ALLKE, ALLVD
*ENERGY OUTPUT, PER ELEMENT SET, ELSET=Rebars2
 ALLIE, ALLSE, ALLPD, ALLCD, ALLAE, ALLDMD, ALLDC, ALLFC, ALLKE, ALLVD
**
*END STEP
```

European Commission

EUR 24151 EN – Joint Research Centre – Institute for Energy
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Author(s): Oliver Martin
Luxembourg: Office for Official Publications of the European Communities
2010 – 38 pp. – 210 x 297 cm
EUR – Scientific and Technical Research series – ISSN 1018-5593
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DOI 10.2790/19763

Abstract

This EUR report describes numerical missile impact analyses on a reinforced concrete slab performed at JRC-IE using the Finite Element (FE) solver ABAQUS/Explicit. The FE model of the impacted reinforced concrete slab resembles a structure used in the missile impact tests by Hanchak et al. FE analyses with a hard (rigid) and a soft (deformable) missile are performed. Traditional Lagrangian formulation for both the missiles and reinforced concrete slabs are used. Two different build-in constitutive models for concrete in ABAQUS/Explicit, the Brittle Cracking Model and the Concrete Damaged Plasticity Model, are compared with each other and their suitability and limitations for missile impact analyses are explored. It turns out that only the Concrete Damaged Plasticity Model in combination with a soft missile leads to physically reasonable and sound results in terms of strains/stresses of the reinforced concrete slab, overall energy balances and overall deformation of the concrete slab when a traditional Lagrangian formulation is used for both missile and reinforced concrete slab.

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