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A methodology to calibrate structural finite element models for reinforced concrete structures subject to blast loads

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ABSTRACT: Civil buildings are not specifically designed to support blast loads, but it is important to take into account these potential scenarios because of their catastrophic effects, on persons and structures. A practical way to consider explosions on reinforced concrete structures is necessary. With this objective we propose a methodology to evaluate blast loads on large concrete buildings, using LS-DYNA code for calculation, with Lagrangian finite elements and explicit time integration. The methodology has three steps. First, individual structural elements of the building like columns and slabs are studied, using continuum 3D elements models subjected to blast loads. In these models reinforced concrete is represented with high precision, using advanced material models such as CSCM_CONCRETE model, and segregated rebars constrained within the continuum mesh. Regrettably this approach cannot be used for large structures because of its excessive computational cost. Second, models based on structural elements are developed, using shells and beam elements. In these models concrete is represented using CONCRETE_EC2 model and segregated rebars with offset formulation, being calibrated with continuum elements models from step one to obtain the same structural response: displacement, velocity, acceleration, damage and erosion. Third, models based on structural elements are used to develop large models of complete buildings. They are used to study the global response of buildings subjected to blast loads and progressive collapse.
This article carries out different techniques needed to calibrate properly the models based on structural elements, using shells and beam elements, in order to provide results of sufficient accuracy that can be used with moderate computational cost.

KEY WORDS: Blast; Reinforced Concrete; Waffle Slab; Shells; Beams; Frame-type Building, Progressive Collapse.

1 INTRODUCTION

In recent years a number of civil buildings have been subject to explosive loads, caused by accidental events or terrorist attacks. In the design of these buildings, usually made of reinforced concrete (RC), these actions had not been taken into account. This underlines the importance of analyzing the vulnerabilities of such buildings, enabling also to check possible design improvements. Such evaluations may be carried out with the help of advanced computational procedures of the nonlinear dynamic phenomena involved.

Some examples of catastrophic explosive events on buildings are mentioned following. The terrorist attack in Oklahoma City USA [1] on the Alfred P. Murrah Federal Building in April 19 1995 claimed 168 lives and injured more than 680 people. Some 2300 kilograms of ANFO explosive were used, destroying or damaging 324 buildings within a sixteen-block radius. The building suffered enormous damage although it didn't collapse.

The AMIA (Argentine Israelite Mutual Association) building in Buenos Aires was attacked in July 18, 1994 [2], 85 people were killed and hundreds were injured. 275 kilograms of ammonium nitrate fertilizer and fuel oil explosive mixture were used in this attack. The blast totally destroyed the exposed load-bearing walls and led to progressive failure of the floor slabs and collapse of the building.

One of the parking buildings of Terminal 4 in Madrid Airport in Spain was attacked in December 30, killing two and injuring 52 people; 500 to 800 kilograms of an unknown kind of explosive, probably a mix of ammonium nitrate and hexogen caused the explosion that produced collapse of almost all five floors [3].

One explosion causing collapse of the structure happened in Astrakhan, Russia, in February 2012. An accidental gas explosion occurred inside an apartment in the fourth floor of a ten floors building. The ten floors collapsed causing ten dead and twelve injured.

In the last years the interest to analyze blast loads in civil buildings has increased. Luccioni et al [2] [4] (2003, 2004) studied the terrorist attack against the AMIA in 1994. They used explicit dynamic analysis with fluid-structure interaction in AUTODYN [5], through a homogenized material model, and estimated structural damages and progressive collapse. Another example is the work of Krauthammer [6] (2007) that studied the progressive collapse in a complete building using ABAQUS/Explicit [7] code.

In this work, we develop a strategy and models for numerical simulation of buildings subject to blast loads. These scenarios are of very short duration, produce highly nonlinear actions often with local failure of elements, and require the consideration of wave propagation effects. The computational techniques best suited are the explicit dynamic codes, such as LS-DYNA [8] used in this work. LS-DYNA uses a Lagrangian finite element mesh with explicit time integration, which can be used to model complete RC buildings and their progressive collapse [9].

It is possible to perform detailed local analyses of selected elements or parts of a building. These models typically use a Lagrangian mesh with non-linear continuum elements for the concrete and non-linear beam elements for segregated representation of steel reinforcement constrained within the concrete. Such detailed models are not feasible for a full building analysis and its progressive collapse due to computational cost and other practical considerations. For simulation of the progressive collapse of a full building a different approach is required. In this work we propose to use structural elements (shells and beams) for concrete and segregated reinforcement, adequately calibrated with detailed local continuum models of selected structural elements, ensuring equivalent structural behavior.

In the remaining of this paper first in section 2 the main characteristics of the continuum 3D elements models are described. In section 3 structural models, using shells and beams, are developed and calibrated with the previous continuum 3D models. In section 4 a model for a full building with structural elements is shown, analyzed for the action of blast load and progressive collapse. Finally, some final remarks are summarized in section 5.

2 FINITE ELEMENT METHODS FOR BLAST LOADS IN RC STRUCTURES

These models represent highly nonlinear dynamic scenarios and require key features in order to provide realistic simulations. It is necessary represent properly the non-linear behavior of reinforced concrete, the blast wave in the air, the wave transmission through columns and slabs, the stress redistribution when any element fails and the process of progressive collapse of the complete building.

2.1 Finite elements

A Lagrangian finite element mesh with explicit time integration is used for the RC structure, within LS-DYNA code. The explosion acts in a range of time between 0.01 and 0.1 ms with high values of applied pressure. A large number of elements in 3D are needed to simulate a complete building. For short times and large 3D applications explicit methods are efficient due to the uncoupled algorithms in which it is not necessary to assemble global matrices for simultaneous equation systems [10]. The Courant condition for stability of explicit integration limits the time step, but this is not a problem in rapid dynamic blast action [11]. However our application considers also the progressive collapse, which takes seconds to develop. The only way to bring down the computational cost is to reduce the detail and the number of elements in the model.

2.2 Concrete models

The CSCM concrete material model [12] for 3D continuum elements can capture the nonlinear behavior of concrete: inelastic response with different behavior in tension and compression, plastic deformation with softening in compression, damage due to smeared cracking in tension and strain rate effects. The LS-DYNA CSCM concrete model has the following properties:

- Used only for continuum 3D type elements.
- Different behavior in tension and compression.
- Three failure or yield surfaces (TXE Tensile, TOR Shear, TXC Compressive).
- Softening in compression with regularisation to achieve mesh objectivity.
- Damage in tension.
- Strain rate effects.
- Erosion.

The minimum definition of the model can be achieved by 4 parameters: mass density, unconfined compression strength, maximum aggregate size and erosion coefficient (elements erode when damage exceeds 0.99 and the maximum principal strain exceeds a given value). The rest of parameters are automatically calculated by the model for ordinary concrete.

Figure 1 shows the response of CSCM material model in uniaxial deformation.

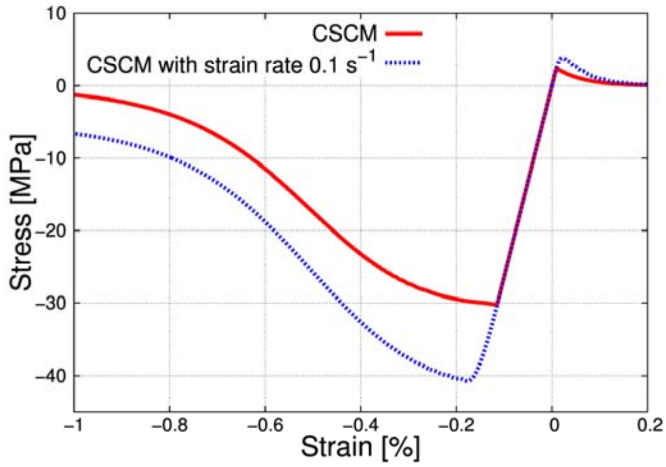

Figure 1. CSCM material for 30 MPa concrete, subject to unconfined uniaxial extension, with and without strain rate effect.

An alternative RC model within LS-DYNA is the EC2 concrete material model, which is applicable for shells and beam elements and also can represent concrete with different behavior in tension and compression, plastic deformation with softening in compression and damage due to cracking in tension.

The EC2 concrete model [13] has the following properties:

- Used only in shells and beam type elements.
- Softening in compression.
- Damage in tension.
- Different behavior in tension and compression.
- Erosion with MAT_ADD_EROSION formulation.
- No strain rate effects.
- Distributed steel reinforcement can be included in material homogeneously.

Figure 2 shows the response of EC2 material model in uniaxial tension and compression.

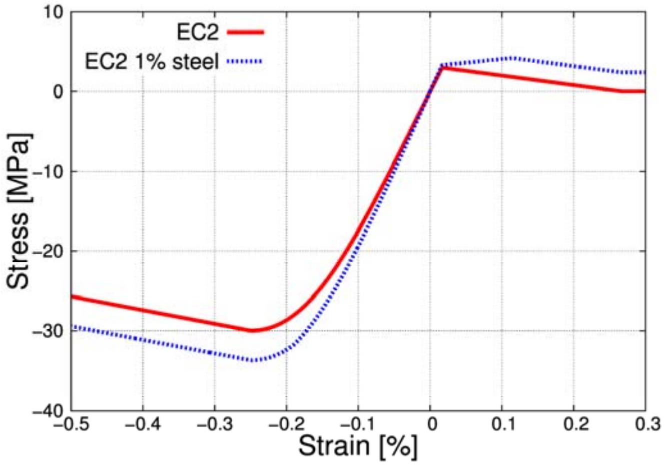

Figure 2. EC2 material for 30 MPa concrete, subject to uniaxial extension, without reinforcement and with 1% of homogeneous reinforcement.

2.3 Steel model and steel-concrete bond

The rebars for RC are modeled with a linear piecewise plasticity model. Its behavior is shown in figure 3.

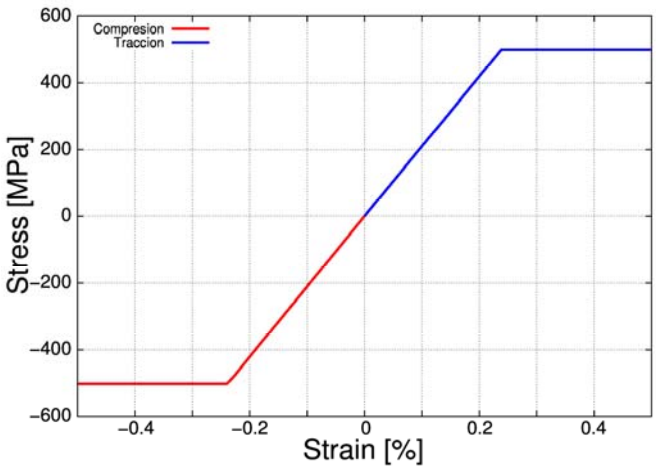

Figure 3. Stress-strain diagram for linear piecewise plasticity model for 500 MPa steel rebar.

Two options are available to model the steel-concrete bond. The first one is merge common nodes between steel and concrete elements. The second option is to embed the rebars within the continuum with full kinematic compatibility using the CONSTRAINED_LAGRANGE_IN_SOLID [14] option implemented in LS-DYNA.

This option has an important advantage, as no coincident nodes of concrete and steel are needed. This implies that the size of concrete continuum elements are not limited by the rebar geometry and position, which leads to reduced computational cost.

Figure 4 shows the mesh of a validation example in order to check the constrained Lagrange in solid formulation. The rebar is modeled with beam elements and concrete is modeled with continuum elements. The model is tensioned and the forces applied in each material are calculated. Both materials deform together until the concrete fails and the full load is transferred to the steel. With this method the adherence between concrete and rebars is not taken into account, which is a limitation of the model.

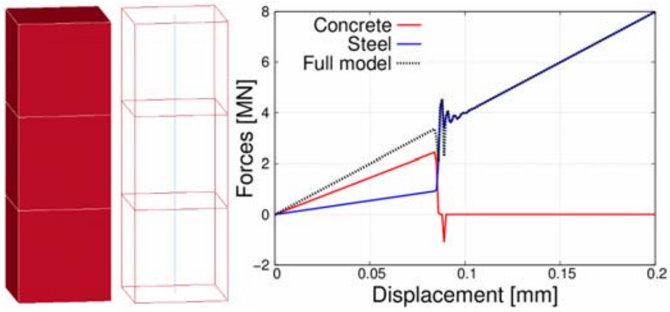

Figure 4. Constrained Lagrange in solid validation.

2.4 Blast

The last major ingredient needed in the model is the blast action. Its load is defined with a pressure law that depends on time and position for each quantity of explosive.

Several approaches may be used to apply the pressures generated by the explosion to the structure. The first method is to use an empirical analytical formulation such as the CONWEP formulation of TM-855-1 [15]. A second procedure is to use fluid-structure coupled methods with simulation in of the blast wave in the air by CFD models [16]. Finally, a third method is to use a mixed methodology CONWEP-CFD [17].

The second and the third methods defined above require very large computational cost for realistic models of buildings. For practical reasons in this work we use the *load blast enhanced* LS-DYNA formulation [13] which implements the CONWEP models [18].

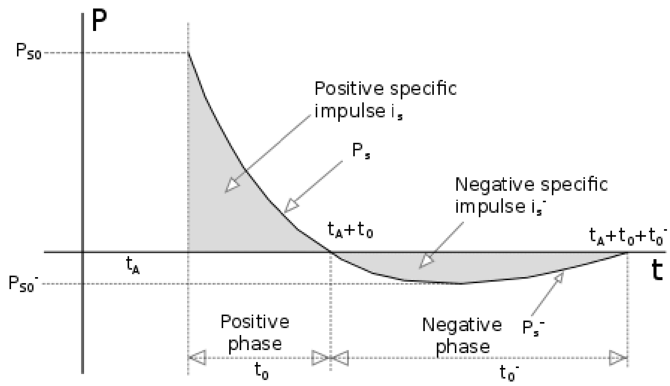

Figure 5. Pressure vs time curve for blast wave in air.

2.5 Continuum 3D elements models

The material models described above may be used within 3D finite element continuum models. Unfortunately, due to excessive computational cost, it is not feasible to simulate complete buildings with these detailed models. However, local models for parts such as columns, slabs or beams may be analyzed in detail.

A representative model for a column is chosen first. The material is 40 MPa concrete, with twelve longitudinal steel bars of 20 mm diameter and transverse reinforcement of 8 mm, steel B500S in all cases. The column is 3.15 m length and 45 × 45 cm section. Figure 6 shows the mesh for concrete (CSCM model) and reinforcement. The *constrained Lagrange in solid* formulation is used for the bond. The effects of blast load on this column are presented in the next section.

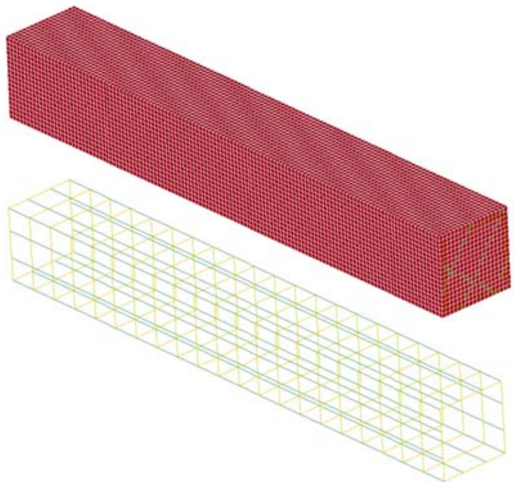

Figure 6. FE mesh for column (concrete and rebars).

The other representative structural element we present here is a waffle slab common in RC buildings. This type of slab incorporates an orthotropic grid of stiffening beams below a thin solid slab. It includes a complex reinforcement setup, which is not detailed here due to lack of space. The slab considered is 8 × 8 m in size, of 30 MPa concrete and B500S steel rebars, with 80 × 80 cm grid spacing and 38 cm thickness. It includes a complex reinforcement layout with top and bottom layers in the beams, which is not detailed here due to lack of space. The material model is the same as for the column (CSCM for concrete, piecewise linear plasticity for rebars and *constrained Lagrange in solid* bond). Figure 7 shows the mesh employed for this model, results will be presented in the next section.

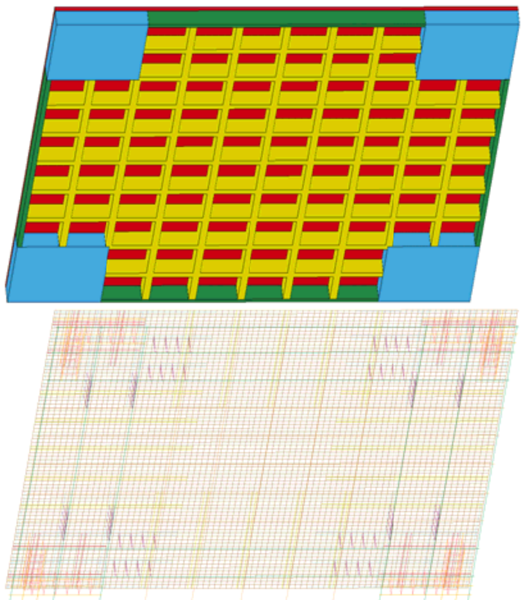

Figure 7. FE mesh for floor slab (concrete and rebars).

3 STRUCTURAL ELEMENT MODELS FOR BLAST LOADS

An alternative to the detailed 3D continuum models described above is to use structural elements (such as beams or shells). These elements incorporate kinematic assumptions, which reduce greatly the number of degrees of freedom, at the expense of less detail in the analysis. For the global simulation of say a complete building undergoing a long-term process such as progressive collapse these models are in fact the most practical alternative. If an adequate calibration is performed with more detailed 3D local models they can provide realistic simulation results.

In the case of LS-DYNA the CSCM material is not available for structural elements, which leads to choose as alternative the EC2 concrete model. Steel rebars are likewise modeled with piecewise linear plasticity. It is possible to include reinforcement in two ways: as a distributed homogenized mixture, or as segregated individual rebars. The bond between steel and concrete is achieved by merging nodes of both meshes. In order to incorporate the geometric eccentricity of rebars, the LS-DYNA option BEAM_OFFSET [13] is used [19].

For the case of the column the model proposed here is formed by 2 joined orthogonal concrete shells with offset beams for reinforcement. The shell element sections are adjusted to the same mass and inertia as the continuum model, and the longitudinal reinforcement is modeled with eccentricity using beam-offset formulation. The transverse reinforcement is not modeled, but it is possible to include an approximation as distributed homogeneous reinforcement.

Figure 8 compares the responses of continuum and structural column models for a blast of 400 kg TNT at 4 m, for the deflection at the center of the column. The correlation between both models is good.

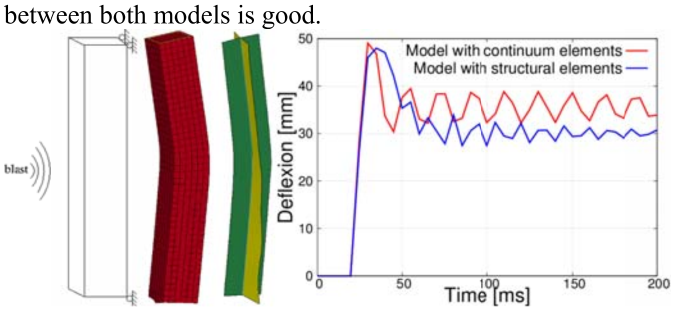

Figure 8. Comparison of column behavior between models with continuum elements and structural elements.

For the case of the waffle-slab the structural model consists of flat shell elements without joists. The thickness is adjusted to obtain the same mass as in the continuum model. The reinforcement is modeled for each grid element with a fictitious rebar section, which equals the total quantities of reinforcement in each direction, in two layers (top and bottom) with offset beams to represent the eccentricity. Figure 9 shows the comparison of continuum and structural models for a blast load of 200 kg of TNT at 2 m distance under the center of the slab. The results show a good correlation between models, similar damage and erosion patterns, and similar displacement and velocity histories in the center of the slab.

These comparisons validate the use of structural models instead the 3D continuum models with the calibration proposed: EC2 concrete material model, concrete shells sections adjusted to same mass and inertia, fictitious rebar sections with offset formulation and erosion formulation to obtain the same erosion patterns.

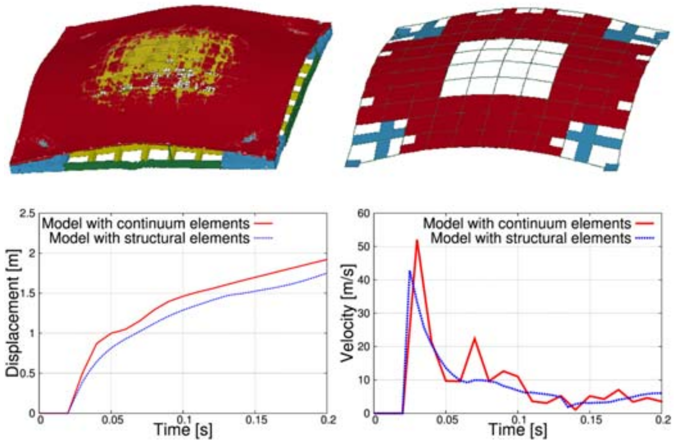

Figure 9. Waffle slab comparison between models with continuum elements and structural elements. Deformed models, displacement and velocity time-histories.

Table 1 shows the computational time employed for the dynamic analysis of the waffle-slab model in both cases. As expected, the computational cost is reduced drastically.

Table 1. Comparison of computer time for slab models using a 12CPU Xeon-X565 computer.

	Number of elements	Calculation time
Continuum element model	180000 bricks and 29000 beams	2 h 50 min
Structural element model	728 shells and 916 beams	55 s

4 BULDINGS UNDER BLAST AND PROGRESSIVE COLLAPSE

The structural models using beams and shells as described in the previous section have been used to develop a model of a 5-story frame-type car-park building. The floor area is 32×32 m with a height of 3.15 m per story. An explosive charge of 800 kg TNT is located in the first block from front and left, 2 m in both horizontal directions from the inside column and 1 m above the first floor.

The simulation of the progressive collapse requires two important additional features: the gravity load and the impact between floors in the falling process. Gravity is taken into account by the self-weight of each element. It is important to remark that the physical time for simulation is several orders of magnitude greater than the time taken by the blast load and damage process itself. Contact is considered using the automatic general contact formulation [13] in LS_DYNA. The increased simulation time as well as the computation of contacts needs likewise larger computational resources. However, these costs are feasible for a structural element model such as proposed here.

Figure 10 shows a sequence of collapse for the complete building model. First the blast load produces deformations, failures and erosion in elements near the explosive charge; following the gravity causes the elements which are no longer supported to fall; then several elements are dragged by the falling parts and impact with other parts below, causing approximately a quarter of the building to collapse.

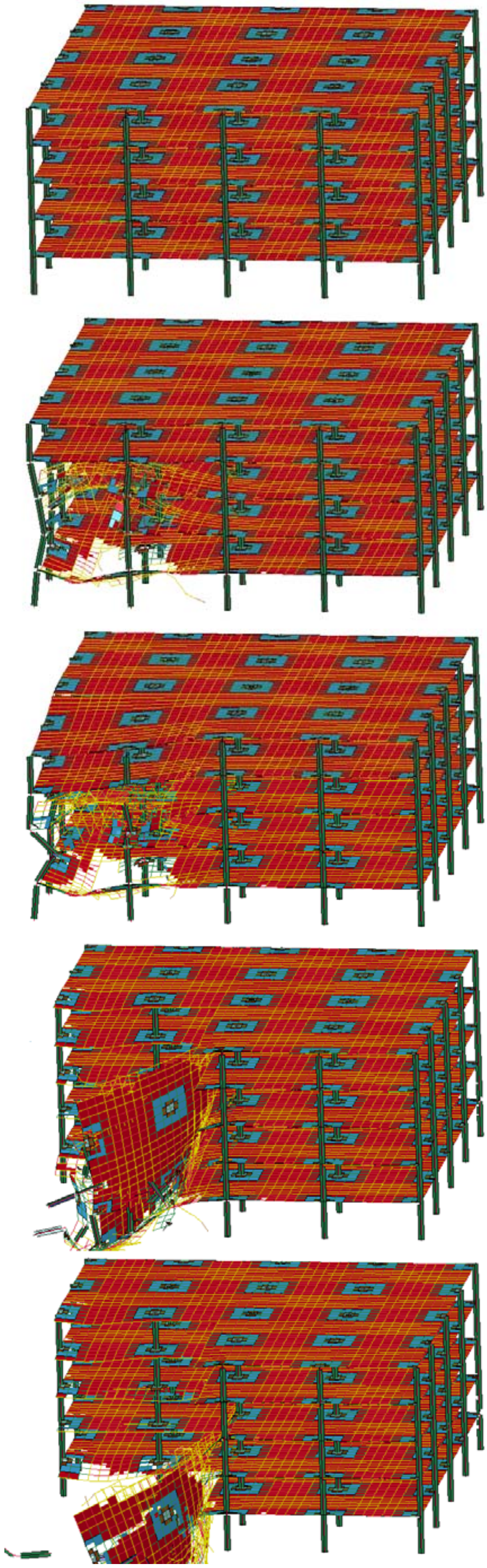

Figure 10. Building collapse. Time of blast initiation: 0.02 s. Deformed model at 0 s, 0.5 s, 1.5 s, 3.5 s and 4.5 s.

Some limitations must be acknowledged for the above models. These do not consider properly the blast pressure in a subsequent floor when a previous floor is damaged and the blast wave passes through it. The blast energy loss in the process of slab rupture is not simple to evaluate. This could be computed with a Lagrangian-Eulerian (ALE) mesh for blast propagation in the air. In this example the blast load has been applied in the third floor ignoring the second floor, but an ALE model could evaluate more precisely this pressure load, at the expense of a huge computational cost. Another problem is that some parts of the concrete slabs become projectiles and impact on the structure. The erosion in the shells elements needed to simulate the damage in the structure produces fewer projectiles than in reality.

5 CONCLUSIONS

We present a strategy for modeling blast scenarios based on structural elements, using available material models for structural elements and techniques to include the reinforcement in a realistic way. These models are calibrated against full three-dimensional models and shown to be accurate enough. At the same time they provide the basis for realistic simulation of explosion and progressive collapse in full-scale buildings. The following concluding remarks may be summarized:

- Structural elements are needed for practical simulation models for complete RC buildings, with reasonable computational costs.
- Structural elements models must be calibrated against full 3D models to accurate enough models.
- The structural elements models provide an approximate global solution; for detailed local analyses of structural parts 3D continuum elements models may be used.
- This strategy can be used to evaluate damage in structures caused by blast loads and to test design improvements on future buildings.
- The effects of progressive collapse can be estimated in order to obtain safe designs.

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