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IMPACT AND EXPLOSIVE LOADS ON CONCRETE BUILDINGS USING SHELL AND BEAM TYPE ELEMENTS

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Abstract. *The threat of impact or explosive loads is regrettably a scenario to be taken into account in the design of lifeline or critical civilian buildings. These are often made of concrete and not specifically designed for military threats. Numerical simulation of such cases may be undertaken with the aid of state of the art explicit dynamic codes, however several difficult challenges are inherent to such models: the material modeling for the concrete anisotropic failure, consideration of reinforcement bars and important structural details, adequate modeling of pressure waves from explosions in complex geometries, and efficient solution to models of complete buildings which can realistically assess failure modes.*

In this work we employ LS-Dyna for calculation, with Lagrangian finite elements and explicit time integration. Reinforced concrete may be represented in a fairly accurate fashion with recent models such as CSCM model [1] and segregated rebars constrained within the continuum mesh. However, such models cannot be realistically employed for complete models of large buildings, due to limitations of time and computer resources. The use of structural beam and shell elements for this purpose would be the obvious solution, with much lower computational cost. However, this modeling requires careful calibration in order to reproduce adequately the highly nonlinear response of structural concrete members, including bending with and without compression, cracking or plastic crushing, plastic deformation of reinforcement, erosion of vanished elements etc.

The main objective of this work is to provide a strategy for modeling such scenarios based on structural elements, using available material models for structural elements [2] and techniques to include the reinforcement in a realistic way. These models are calibrated against fully three-dimensional models and shown to be accurate enough. At the same time they provide the basis for realistic simulation of impact and explosion on full-scale buildings.

1 INTRODUCTION AND MOTIVATION

The threat of impact or explosive loads is regrettably a scenario to be taken into account in the design of lifeline of critical civilian buildings. These are often made of concrete and not specifically designed for military threats. In the last years there were several cases in which civil buildings were the target of terrorism attacks.

Oklahoma City bombing [?] on April 19, 1995 in USA can show the destruction that can be caused by bombing attack. In this case 2300 kilograms of ANFO were used; The blast claimed 168 lives and injured more than 680 people; the blast destroyed or damaged 324 buildings within a sixteen-block radius. The Alfred P. Murrah Federal Building was the target; the building suffered several/enormous damages although it didn't collapse.

The Asociación Mutual Israelita Argentina (AMIA; Argentine Israelite Mutual Association) building in Buenos Aires was attack on July 18, 1994. In this attack 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, led to progressive failure of the floor slabs and collapse of the building.

The parking of the Terminal 4 of the Madrid-Barajas Airport in Spain was attacked on December 30, when a van bomb exploded in, killing two and injuring 52 people; 500 to 800 kilograms of an unknown kind of explosive, probably a mix of ammonium nitrate and hexogen cause the explosion that demolished almost all of the five floors of the car park and produced around 40 tones of debris [4].

The 2009 Burgos bombing occurred on July 29, 2009, when at least 65 people were injured after a van bomb carrying more than 300 kg of explosive went off outside a Civil Guard barracks in the northern city of Burgos, Spain.

This four examples shows the importance of the blast loads in order to design critical civilian buildings. In general, the measures taken to avoid those threats focus on prevent that a significative quantity of explosives could be close of those buildings. Recently several research was made in order to modeling the past terrorism attacks [3], simulate blast on concrete structures [5] and to explain the progressive collapse of civil structures [6].

With this orientation this work present a strategy for modeling frame-buildings subject to blast loads, in order to provide sufficient accuracy results for choose between structural designs and to estimate the amount of explosive that one building can resist without collapse.

1.1 Numerical models for simulation and allow evaluation of structural alternatives

Numerical simulation of such cases may be undertaken with the aid of state of the art explicit dynamic codes. This codes, like LS-Dyna [2] used in this work, are available methods to study blast loads through very short times in witch they apply. LS-Dyna use a lagrangian finite element method with explicit time integration, that can be used to model, in this case, complete concrete structures.

The computational cost of this method depends essentially on the minimum size of the model elements, number of elements and on time simulation. It is possible, in computational costs, analyze a small part of one building with very accuracy lagrangian finite element method using non-linear continuum elements for concrete modeling and non-linear beam elements for steel reinforcement modeling, constrained in concrete continuum elements, in a model with geometries of each part (columns, beams and slabs) very close to real. But the computational cost is excessive in the case of full building analysis. In the way of full building analysis it's necessary other approximation. This work propose use structural elements (shells and beams) for concrete and reinforcement in segregate way for a low computation cost model that have approximately the same structural behaviour.

1.2 Requirements for modeling

However several difficult challenges are inherent to such models: the material modeling for the concrete anisotropic failure, consideration of reinforcement bars and important structural details, adequate modeling of pressure waves from explosions in complex geometries, and efficient solution to models of complete buildings which can realistically assess failure modes.

The model must be able to represent accuracy the global structure behaviour. This include the wave transmission through columns and slabs, the stress redistribution when any element reach the elastic limit and plastify, the stress redistribution and the appearance of new action due to the erosion of structural elements or parts of them, and the process of progressive collapse of the complete building.

The model must be able to evaluate the action of different quantities of explosive the must be applied in different positions in the building. The blast is a short action (the application time range is in 0.01 to 0.1 milliseconds) and, depends of quantity and distance, high values of applied pressure can be reached.

The reinforcement concrete have a heterogeneous behaviour, caused by two different material working together. So the model must represent properly this behaviour. Using an homogeneous model is more limited the using segregated elements. In the other hand, modeling concrete and steel in segregated elements needs an interface in order to work together.

Concrete has complex behaviour, it is a no-linear material with different behaviour in tension and compression, plastic deformation with softening in compression and damage due to cracking in tension. Additionally there is an increment of elastic limit due to strain rate, and the fail of concrete can be controlled in model by element erosion. Concrete has other properties like fatigue and retraction but those are not important for our application.

And steel is a no-linear material too, with same behaviour in tension and compression and with increment of elastic limit due to strain rate. It plastify when the elastic limit is reached and when the strain is enough it fail.

The material models must represent accuracy the behaviour described above and there must be an model interface to make both materials work together.

2 MATERIAL BEHAVIOR AND ELEMENT FORMULATION

This chapter is dedicated to describe the models and formulation we use to obtain a sufficient approximate behaviour in reinforcement concrete on blast actions.

2.1 Concrete

For concrete we use two different materials models. The first one is used for continuum elements and the second one is used for structural elements (shells and beams).

Continuum element model: The model used for continuum elements is the CSCM LS-Dyna model [1]. This material is able to represent the complex behaviour described above (figure 1). It can be used only in continuum elements.

- Isotropic behaviour.
- Different behaviour in tension and compression.

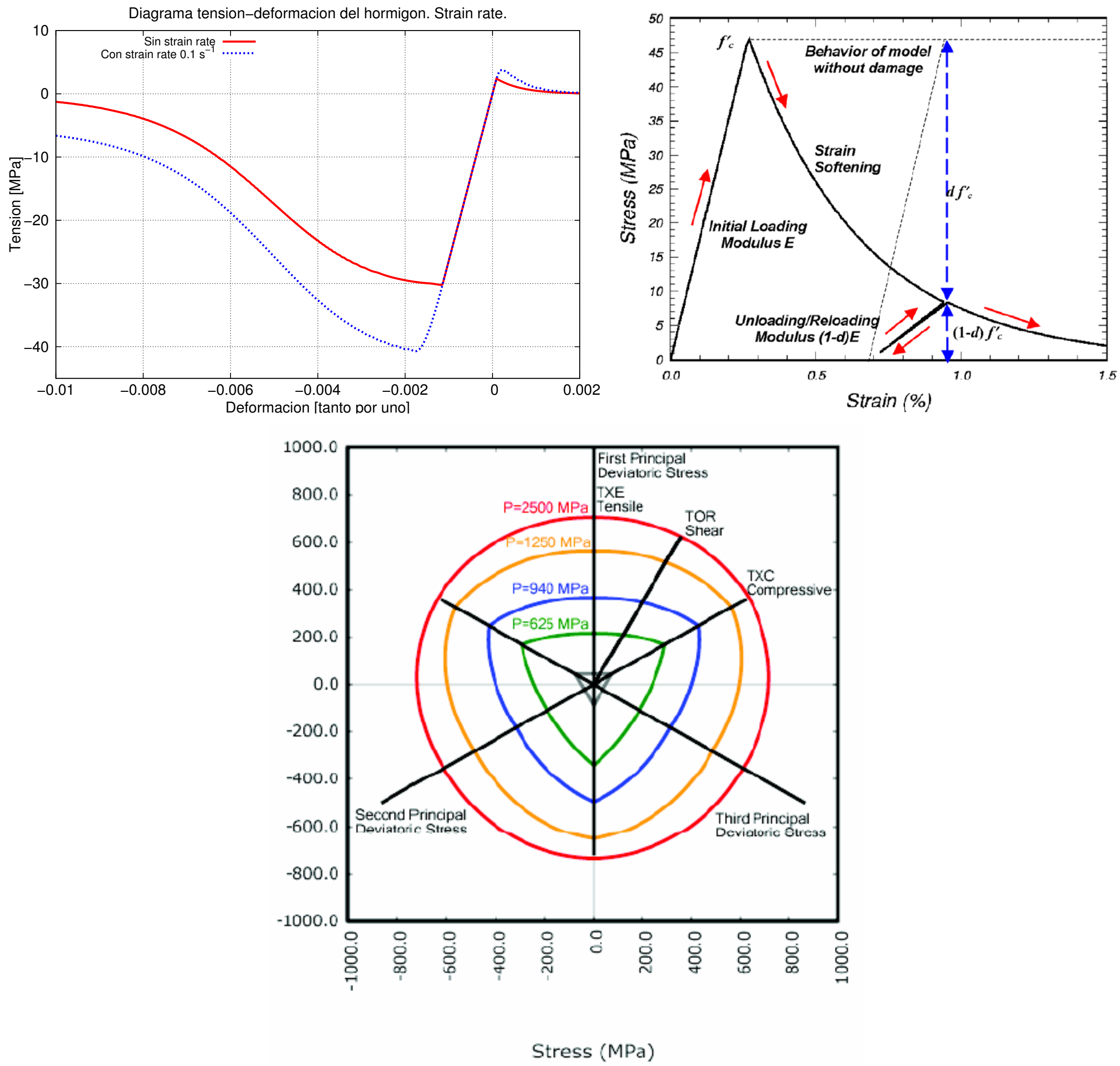

Figure 1: Properties of CSCM concrete model [7]

- Plastity surfaces (TXE Tensile, TOR Shear, TXC Compressive).
- Softening in compression.
- Damage in tension.
- strain rate effects.
- Erosion

Structural element model. Shell and beam model: The model used for structural elements is the EC2 LS-Dyna model [7]. It can be used in shell and beam type elements. Figure 2 show the tension-deformation diagram.

- Softening in compression.
- Damage in tension.

- Erosion with mat add erosion formulation (not by itself).
- No strain rate effects.
- Plastify surfaces.
- Quantities of steel reinforcement cam be included in material homogeneously.

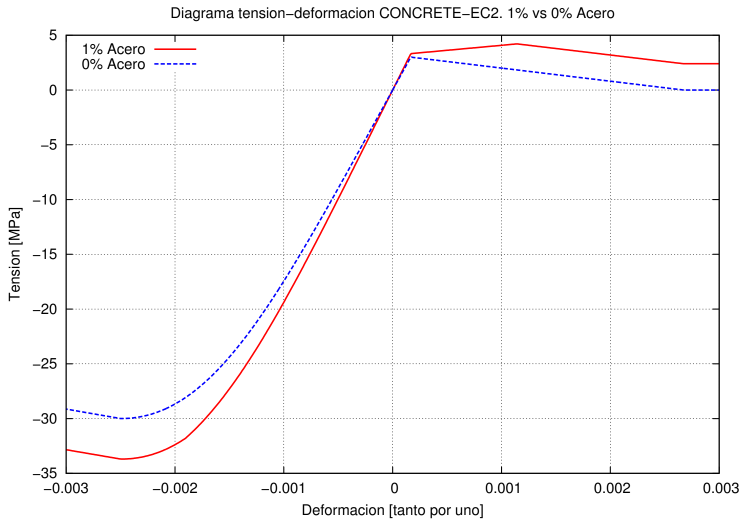

Figure 2: Properties of EC2 concrete model

2.2 Steel reinforcement:

We use the piecewise linear plasticity LS-Dyna model [7] to represent rebar in concrete. This model represents perfectly the behaviour we need for steel reinforcement, with plastic deformation, strain rate effects and fail. We use it in beam elements.

2.3 Concrete/steel interface:

We use two options to model the interface. The first one is merge common nodes between steel and concrete elements, and the second one is use the constrain lagrange in solid [7] formulation implemented in LS-Dyna.

The constrain lagrange in solid option has one advantage: no coincident modes of concrete and steel are needed. This implies that the size of concrete continuum elements are no limited by the rebar geometry and position, that cause low computation cost. In the other hand this option can not be applied for concrete structural elements.

The figure 3 shows the mesh of validation example for the evaluation of proper behaviour of constrain lagrange is solid formulation. Rebar is model with beams elements and concrete is model with continuum elements. We check the global behaviour is correct.

In this way we use the constrain lagrange in solid formulation for continuum models and the mode merge option for structural models.

There are a limitation in both methods: the adherence is not modelized but we assume this limitation.

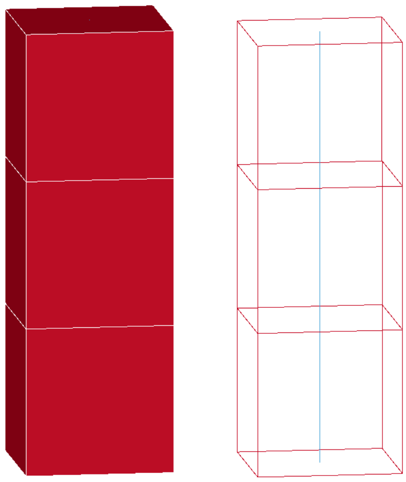

Figure 3: Constrain lagrange in solid

2.4 Offset formulation

In structural models the reinforcement steel beam elements are linked with the concrete shells elements by nodes. It is a problem because all elements are in the same plane, and the influence of reinforcement eccentricity can not be included. To avoid this problem we use a Ls-Dyna beam offset formulation [7] to take account this influence. With beam offset is possible to define a offset distance from the plane in order to correct the position of rebar in model to simulate the real position. The table 1 shows the check of this formulation in a simple beam test model.

Eccentric Reinforcement		
Case	Reaction	Description
Theory B	25.9 kN	Bernouilli beam
Theory T	22.1 kN	Timoshenko beam
Beams	26.9 kN	Beams elements
Shells	25.5 kN	Shell and beam elements

Table 1: Validation offset beam formulation.

2.5 Blast formulation

The blast load is defined with a pressure law that depend on time and position for each quantity of explosive.

In this work we use the blast LS-Dyna formulation [8] that it is the implementation of CONWEP formulation of TM-855-1 manual from U.S. Department of the Army [9].

3 APPLICATION: EXPLOSIVE LOADS ON STRUCTURAL ELEMENTS

Material and element formulation make possible to analyze structural elements of a real frame-type building. The objective of this section is to analyze structural elements of frame-type buildings and check the viability of use structural finite elements with the same structural response.

There are three main structural elements forming part of a frame-type building: columns, beams and slabs.

In order to analyze this structural elements two models were develop. In first place, continuum elements model was develop, which represents the better characterization of the real quasi-static and dynamic behaviour, and in second place a structural finite elements model was develop, which have the similar structural behaviour and low computational cost. Similar structural behaviour for second model is achieved with properly geometry and materials models parameter adjustment.

3.1 Column

In order to analyze columns on frame-type buildings we choose a representative one which is testing in two ways: quasi-static an dynamic. Bending perform the quasi-static analysis and three different cases with two quantities of explosive perform the dynamic analysis.

We use a simply supported 40 MPa concrete column with twelve longitudinal reinforcement bars of 20 mm diameter and transversal reinforcement of 8 mm, and steel is type B500S. The column is 3.15 meters length and 45×45 centimeters section Column mesh and reinforcement for continuum elements model are showed in figure 4.

We develop two models of continuum model using CSCM concrete material for continuum elements and piecewise linear plasticity for reinforcement beam elements: the first one with the constrain lagrange in solid formulation to model the interface, with bigger elements in the mesh, and the second one with merge nodes of common elements, with the necessary smaller elements. We check both models to be ensure the constrain lagrange in solid formulation model has the same structural response than the merge nodes model. In the successive we use the constrain lagrange in solid model due to its low computational cost.

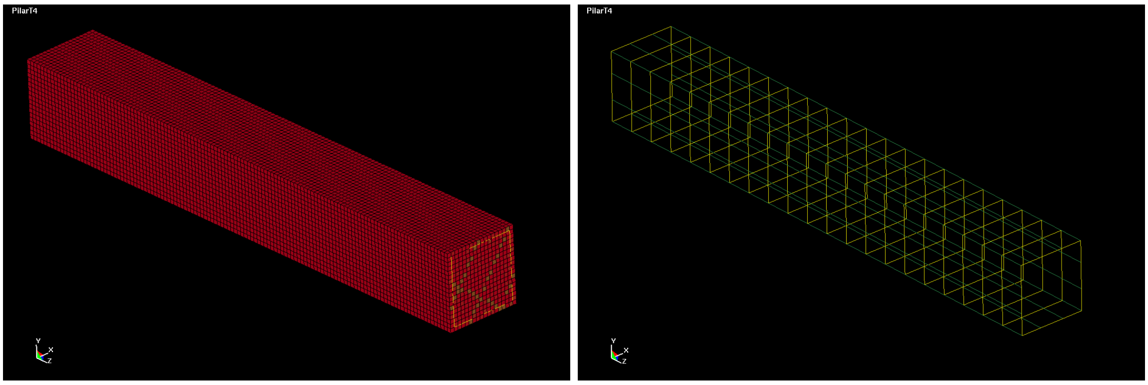

Figure 4: Column mesh and reinforcement for continuum elements model

For the structural model we develop a concrete shell model with offset beams witch nodes are merged in the cross node shells (figure 5a). The geometry properties of the shell elements are adjustment to have the same mass and inertia than the continuum model, and the longitudinal reinforcement is model in the real position with the aid of offset beam formulation. The transversal reinforcement are not model, but it is possible to include it in the EC2 concrete material model like a fraction of steel reinforcement. It is possible too develop a model with concrete beam elements, but this model, only with beam elements are unable to recibe the blast action. This is the reason to use shell elements for the structural model.

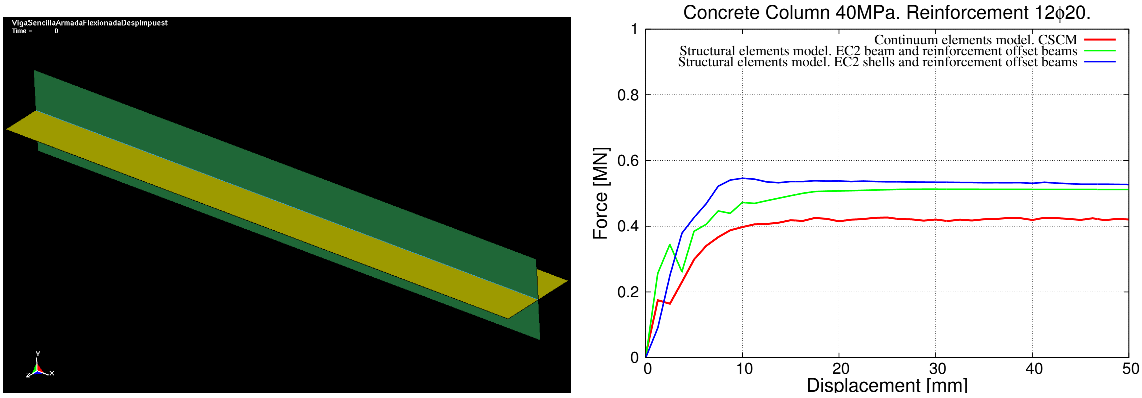

Figure 5: Column mesh for structural elements model and bending comparison column models

Quasi-static bending comparison: The figure 5b shows the response of continuum element model (red line) and structural shell element model (blue line) for a prescribed motion that produce the bending in the column. In this graphic we see that there is a good correlation between models. The structural model is more rigid than the continuum model despite it have not the transversal reinforcement. It is due to in the progressive plastify of continuum elements through the column section in continuum model, whereas the structural model with less elements in section become more rigid until the elements plastify.

Blast action. Dynamic response comparison: We must check the dynamic response to blast action in both models like the quasi-static response. In this case, we compare the response to different quantities of explosive and distances. The structural response is quite different depends on explosive quantity and distance: For incremental quantities of explosive the column have more and more damage, in first place the concrete in the rear of blast impact face plastify, then some elements of this concrete are erosioned, then the rear reinforcement plastify and the concrete plastify is extended to all the column section and finally the column collapse due to full section erosion of concrete and plastify and erosion of rebar.

The figure 6 show the response comparison of continuum and structural models for a quantity of 400 kg of TNT at four meters distance. In this case the rear concrete plastify but it is not eroded. The center column displacement are measure in time and compare in both models. The displacement of structural model is minor than continuum model due to more transversal flexibility but is a good correlation.

The figure 7 show the response comparison of continuum and structural models for a cuantity of 400 kg of TNT at four meters distance. In this case the concrete plastify but it is not eroded. The center column displacement are measure in time and compare in both models. The displacement of structural model is minor than continuum model due to the full erosion of the shells elements whereas in the continuum model remains some concrete elements. We take account of this behaviour and assume less displacement but more damage in structural column model.

3.2 Beam

In the same way column is analyzed we analyze a beam, to ensure there is not differences when the reinforcement is asymmetric. In this case we use a simply supported 40 MPa concrete

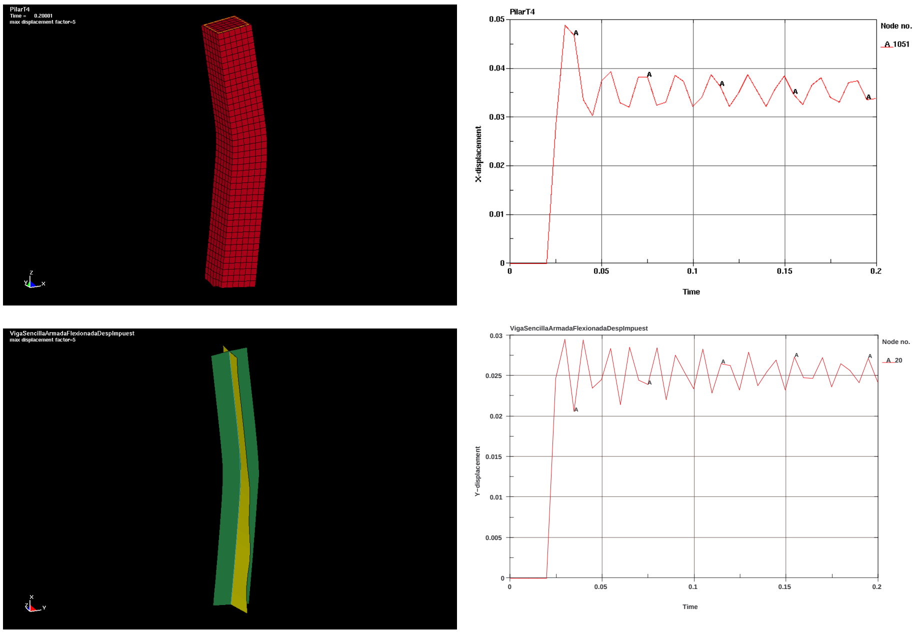

Figure 6: Column deformed mesh and displacement (x5 scaled) in center of column. Continuum and structural models.

column with five longitudinal reinforcement bars of 16 mm diameter in the rear face and five longitudinal reinforcement bars of 12 mm diameter in the front face.

Figure 8 show the comparison of this case for quasi-static bending. It is similar than the column one. The blast results on similar behaviour, with more damage and less displacement.

3.3 Slab

The are some types of slabs that can be used in frame-type buildings, we study the waffle slab case. This type of slab uses prefabricated hollow sheet metal or plastic domes to create a grid pattern of voids in a solid floor slab. It have several reinforcement bars, with various sections, in different positions, both sides. This case is complex due to complex reinforcement layout and the concrete geometry.

The case we study use 30 MPa concrete and B500S steel reinforcement in a 8×8 meters waffle slab with 80×80 centimeters hollow sheet domes and 38 centimeters thickness. It have complex reinforcement layout, superior grid, superior and inferior reinforcement in joists.

We develop two models for waffle slab, like in the column case, the continuum model using CSCM concrete material model in continuum elements and piecewise linear plasticity material model in beams elements using constrain lagrange in solid to get work together, and the structural model using EC2 concrete material model in shell elements and piecewise linear plasticity material model in offset beams elements using merge nodes option to get work together.

The continuum model show in figure 9 has detailed mesh. All reinforcement bars of real waffle slab are model with beam elements and the hollows geometry of concrete are model with continuum elements. The continuum model use constrain lagrange in solid formulation. In this model is not possible use the node merge option for model the interface between steel and concrete. The complex geometry of the model and the amount of reinforcement bars and their positions led to very small size and elevated number of continuum concrete elements, producing excessive computational cost.

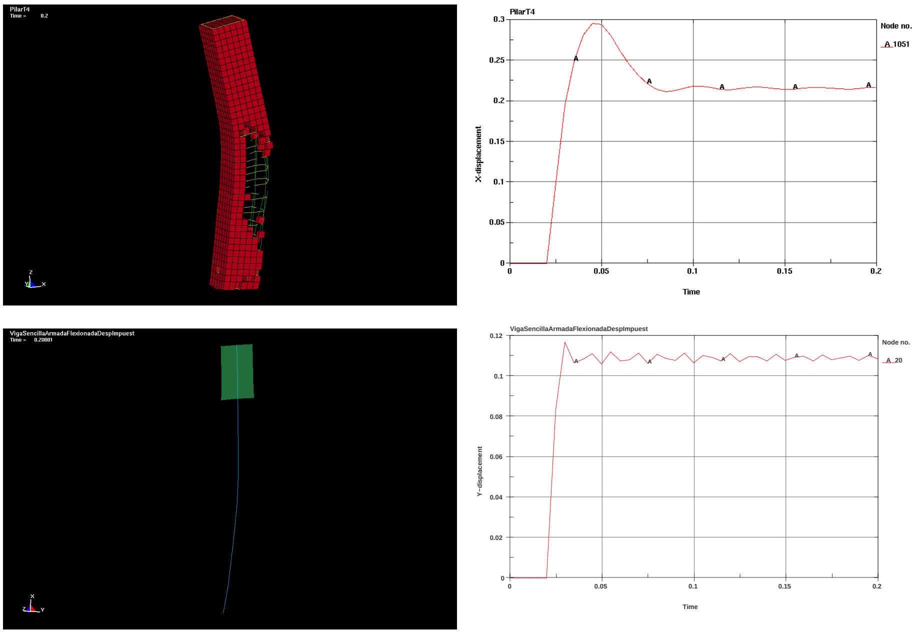

Figure 7: Column deformed mesh and displacement in center of column. Continuum and structural models.

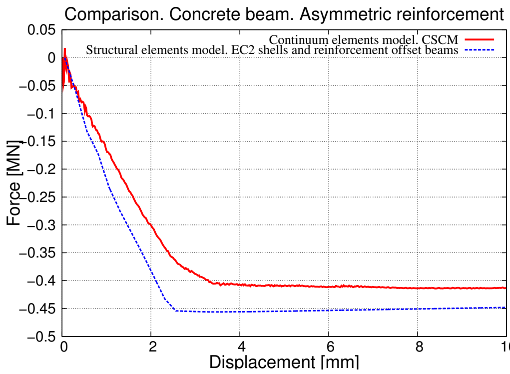

Figure 8: Bending comparison beams models with asymmetric reinforcement

The structural model show in figure 9 has very few elements than continuum model. The concrete is model with shells elements without joists. The thickness of shell elements is calculated to obtain the same mass in continuum and structural models. The reinforcement are model for each dome with a fictional rebar section that represent the total quantities of reinforcement in each direction and differentiate between superior and inferior reinforcement. This fictional rebar are model with offset beams to represent properly the eccentricity of the rebar.

Quasi-static bending comparison: The figure 10 shows the response of continuum element model (red line) and structural shell element model (blue line) for a prescribed motion in the slab center that produce bending. In this graphic we see that there is a rough correlation between models. Both models have peaks in the graphic line of resultant force due to the successive plastify of slab parts. It is difficult obtain the same results in structural model and continuum model. But this rough approximation can provide a range to study the slab behaviour with one

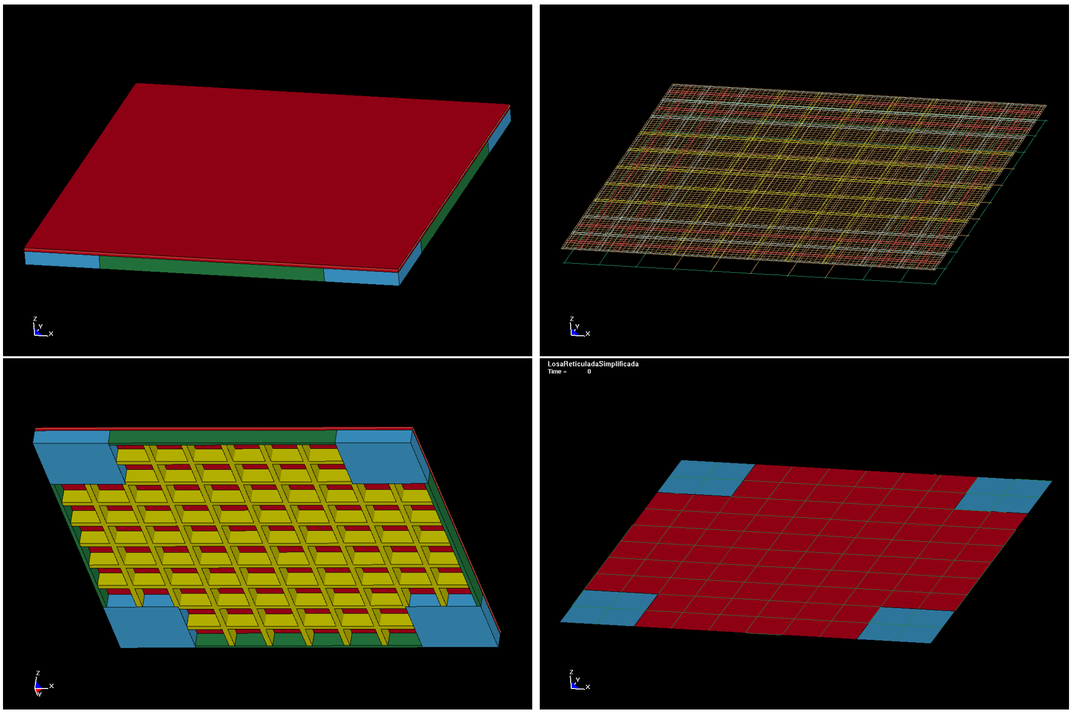

Figure 9: Top left: Mesh of continuum elements waffle slab (top view); Top right: Reinforcement of continuum elements waffle slab; Bottom left: Mesh of continuum elements waffle slab (bottom view). Mesh of structural elements waffle slab (top view)

structural model.

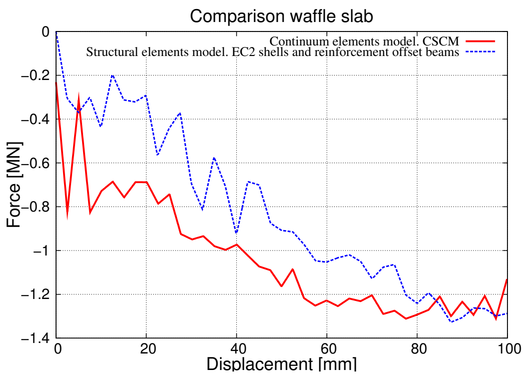

Figure 10: Bending comparison waffle slabs models

Blast action. Dynamic response comparison: We must check the dynamic response to blast action in both models like the quasi-static response. We compare the response to different quantities of explosive and distances. We compare the damage and erosion that is produced in both models.

The figure 11 show the comparison of continuum and structural models for a cuantity of 200 kg of TNT at 2 meters distance from the center of the slab in the inferior side. There is

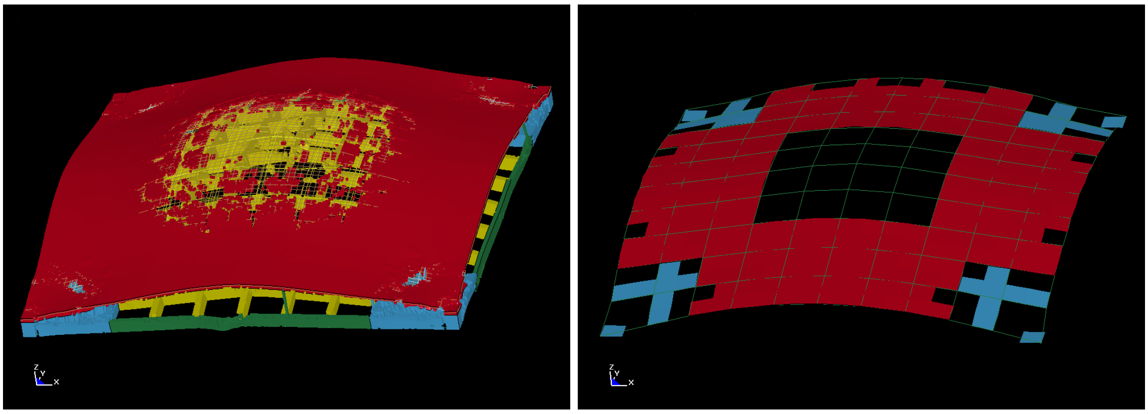

Figure 11: Comparison: deformed mesh in continuum elements model and structural elements model. 200 kg TNT

a good correlation between both models, and we can use the structural model to evaluate the damage produced in a waffle slab from a frame-type building.

4 APPLICATION: FRAME-TYPE BUILDINGS

The final application of this work is evaluate the response of a frame-type building subject to blast action.

Column and slab models are being developed, and it can be use together in the develop of a frame-type complete building. The figure 12 show the model developed for a 3 floors building, with 4×4 waffle slabs in each floor. This model provide us a tool to evaluate the damage caused in a building by blast. In this case a 400 kg of TNT in the first floor center in one slab at 1 meter from the first floor cause the damage show in the figure.

This case can be resolved with moderate computational cost. For this application model calculation time are in the range of 0.1 to 0.5 seconds, sufficient time to evaluate the action of blast in the structure.

There are limitations on the application of this strategy. One of them is that is not possible to evaluate pressure of the blast in a second floor when a previous floor is damaged and the blast wave pass trough it. The blast energy loss in the process of breaking the previous slab is difficult to be evaluated. To avoid this problem it is necessary to use an ALE mesh [11] to evaluate the propagation of the wave trough an air mesh. Other of this problems is that there are some parts of concrete slabs that become projectiles and impact on the structure. The erosion in the shells elements needed to simulate the damage in the structure make few projectiles than be in reality.

This model can be used too to evaluate the possible progressive collapse of the structure, with the inconvenient of more model calculation time, in the range of 3 to 10 seconds for a tree floors building. This causes the CPU calculation time increases, but it can be calculated. Progressive collapse and multiple floor blast analysis are current in develop in the research project we are involved.

5 CONCLUDING REMARKS

We present a strategy for modeling such 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 fully three-dimensional models and shown to be accurate enough. At the same time they provide the basis for realistic simulation of impact

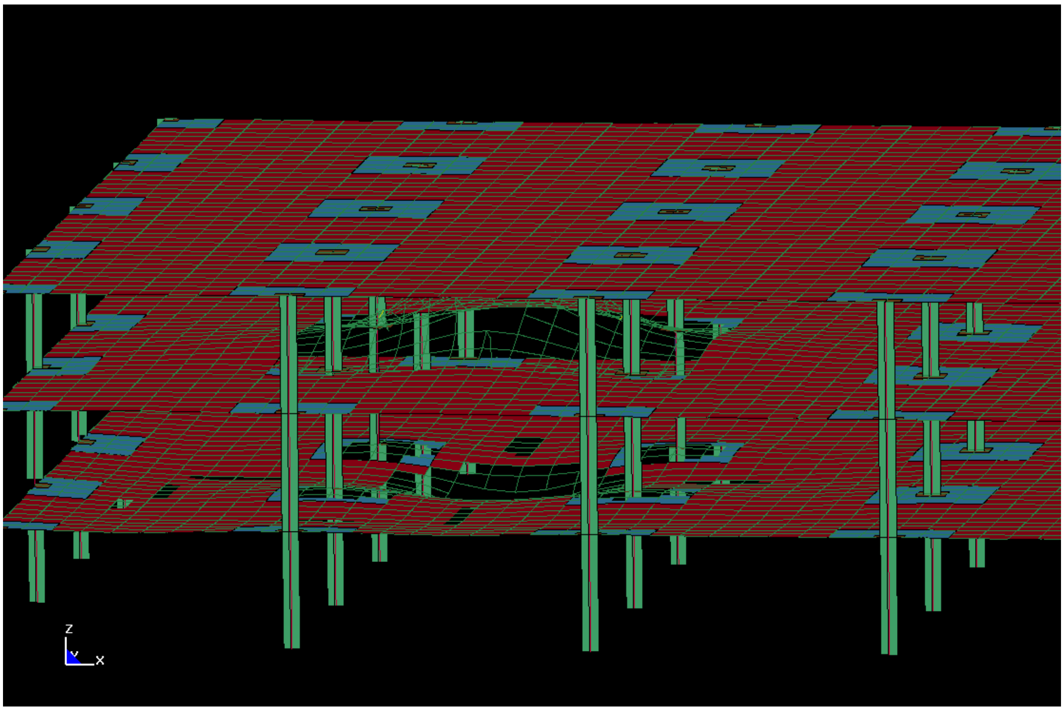

Figure 12: Blast into a frame-type building. 400 kg TNT

and explosion on full-scale buildings.

- Structural elements are needed for full frame-type building analysis due to computational cost.
- Structural elements models must be calibrated against fully three-dimensional models to obtain accurate enough.
- The strategy provide an approximate problem solution, for detailed analysis of structure parts three-dimensional model must be used.
- This strategy has limitations like action evaluation in successive floors and projectile considerations that need further develop. Structure collapse require additional adjustment of models.
- This strategy can be used to evaluate damage in building for blast loading and to test design improves on future buildings.

The studies which are presented herein have been carried out as part of a research project involving the Polytechnic University of Madrid and FHECOR Consulting Engineers, with the financial support of the Spanish Airport Authority (AENA) with the aim of modeling explosion hazards and improving robustness in the design of new structures. The work presented in this paper is but a small part of the research project whose scheduled time duration is 3 years.

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