STRUCTURAL AND LIFE SAFETY ALTERNATIVES IN URBAN LANDSCAPE UNDER EXTREME ACTIONS IN SEISMIC ZONES OF ROMANIA

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ABSTRACT :

The paper investigates alternatives for design and/or strengthening of buildings, for structural and life safety, under extreme loadings, starting from earthquake engineering constraints. The Romanian Earthquake Code P100-1/2006 and EC 8 relate the life safety ultimate state and life safety criteria to collapse prevention through the mean recurrence interval of the design action. The recent EN 1991-1-7:2006 refers only to some accidental actions and internal explosions, but excludes external blasts, military actions and sabotage or tornadoes. The paper aims to cover this gap by a multi-hazard approach, with an integrated design of architectural and structural members. In Romania, many low-rise buildings are stiffer, made of masonry and concrete, while high-rise reinforced concrete structures are slender and are more vulnerable to Vrancea long-period seismic motions. The new urban landscape evolves to higher steel structures, with glass envelopes, atria, covered canopies, outside elevators, underground and overground spaces, where there is a danger of blast pressure and fire spreading on vertical and horizontal direction. Advanced earthquake resistant design is an asset but some members are sight exposed, have higher risk exposure and reduced redundancy to other extreme actions. We have studied plan and volume solutions vs. robustness and progressive collapse criteria and the use of safe rooms against risks caused by collapse or shattering and projection of debris. A strengthening solution was tested in INCERC on masonry specimens under diagonal compression, using CF plates, with good results.

KEYWORDS: *Life safety, structural safety, earthquake, extreme actions, progressive collapse*

1. STATE OF THE ART OF PROVISIONS CONCERNING EXTREME ACTIONS

1.1. State of the art of provisions at international level

For earthquake resistant structures, the best developments are in performance based design, operational for less than a decade in the USA, New Zealand and Japan (ATC, BSSC, NEHRP, FEMA etc). FEMA 273/274 and VISION 2000 (USA) relates the level of performance to damage level, with due reference to occupancy and operational needs, structural and life safety or collapse prevention /robustness. The seismic design code of buildings in Japan was revised in June 2000 to implement a performance-based structural engineering framework. Concerning the expertise on blasts and progressive collapse, until the mid of 1990's, such work was mainly performed for high security facilities. The research on such extreme action showed a new trend in the USA after the repeated hurricanes and terrorist attacks of 1980's on US embassies of 1980's, WTC New York attacks of 1993, A.P. Murrah building blasting in Oklahoma City, 1995 and especially after the destruction of WTC New York Towers on September 11, 2001. Since the maximum pressure decreases as the distance to source increases, the prescription of stand-off areas was the first type of protection to be recommended. Some measures taken have changed the urban landscape (stand-off spaces with concrete blocks, rooms lay-out).

In the European Union, the Directive 89/106/CEE on construction products is associated with EUROCODES for constructions and especially with EUROCODE 8 – Design of structures for earthquake resistance. EU has funded a Performance Based Building Network (2001-2005). For specific aspects, EN 1991-1-7:2006 Eurocode 1 is applied, which refers to accidental actions caused by the impact of autovehicles, ships, helicopters, equipments and explosions (internal, from industrial dust, gases, tunnel accidents). This code excludes external blasts, military actions and sabotage, natural hazards as tornadoes, considering the probability of accidental action bellow 10^{-4} per year. EN 1991-1-7:2006 includes the modelling of risk from extreme actions and (informatively) dynamic design for impact. Large research programmes were financed after the terrorist attacks of Madrid 2004 and London 2005 in main national research establishments and universities in EU. Recent projects of RILEM and EC-COST are a proof of interest.

1.2. State of the art of provisions at national level

Seismic action has a highly destructive potential on Romanian territory. The entire earthquake design code, with seismic coefficients and seismic zonation map have been radically changed after the March 4, 1977 earthquake, and again modified in Code P100-1992. The Romanian Earthquake Code P100-1/2006 is similar to EC 8 and new seismic zoning maps are available. This code is based on the assumption that if the life safety criteria requirements are satisfied for an earthquake having a 100- years Mean Recurrence Interval, one can count as a rule on collapse prevention requirements for an event with 475- years Mean Recurrence Interval. For damage limitation, the seismic action corresponds to an earthquake with a 30- years Mean Recurrence Interval. The Draft Code P-100-3 vol. 2 goes along the same line and prescribes methods of strengthening, with details covered also by a recent INCERC Code on composite materials.

Insofar as structural safety to other climatic actions is concerned, snow and wind zoning maps can be found in specialized codes. Present regulations refer to actions and combinations of natural and conventional technological actions. The drafting of national annexes to European codes is not finished and concerns only some part of actions and structures. Thus, Eurocode EN 1991-1-7 or EN 1996-1-2 does not cover the broad domain of extreme actions. However, there is a new concern on about extreme events as terrorist blasting or large scale technological and transport accidents, or stronger and concentrated storms, very similar to tornadoes, whose damaging effect has been increasing during over last decade, possibly because of acute extreme climatic changes. In Romania this field is not covered by research and adequate technical solutions, although the accession to NATO and EU involves new protection requirements, inclusive against terrorism.

In this respect, an ongoing research on the impact of extreme actions in the current urban-architectural landscape, on structural types and materials of Romania, was directed on specific topics as:

- architectural and structural patterns of the existing building stock and vulnerability under extreme actions;
- selection of new alternative technical solutions for safety of urban assemblies and structures, building envelope, non-structural members, external infrastructures;
- calculations, simulations, laboratory and / or in situ experimental testing on components, materials and models of construction members, with and without protection against progressive collapse;
- evaluating a local concept of safe rooms against shattering and spreading of debris;
- synthesis of integrative technical solutions using advanced technologies and materials, multicriterial cost-benefit and socio-economic evaluation;
- a strategy for risk reduction, with support activities and mechanisms of implementation, for a sustainable development; dissemination through regulations and applications in constructions sector.

2. SPECIFIC OF EXTREME ACTIONS THREATS FOR SAFETY IN URBAN LANDSCAPE

The basic issues in this Research Project are to ascertain:

- the significant extreme actions under new environment conditions;
- the buildings stock and urban landscape vulnerabilities;
- the governing factors for structural and life safety;
- the available and needed required solutions, after a necessary research for new and affordable alternatives.

Vrancea source of intermediate depth produces damage on the S-E half of country, while other crustal sources may struck at local scale in West and North. The magnitude recurrence for Vrancea earthquakes was evaluated to be with return periods of 32 years for M_{G-R} 7, 46 years for M_{G-R} 7.2 and 81 years for M_{G-R} 7.4 . The earthquake of March 4, 1977 (M_w=7.4) was a disaster of national proportions, as a World Bank Report of 1978 estimated the total loss at US$ 2.048 billion. Some recent assessments considered it as possibly equivalent to over 20% of Romania's GDP (Georgescu and Pomonis, 2007). In 1977, out of 40 counties, 23 were strongly affected, with Bucharest recording the highest loss, accounting for 70% of the total, i.e. US$ 1.4 billion. The loss to constructions represented 69.4% of the total or 84.3% of the direct losses; the housing sector losses represented 71.4% of construction losses, or 61.4% of the direct losses and 50.4% of the total losses.

The casualty data referred to 1,578 people killed, 11,321 people injured, with Bucharest at highest human loss, as 90% of the killed and 67% of the injured were there. In Bucharest, casualties were greatly caused by pancake collapse of high-rise buildings with reinforced concrete skeleton and masonry, built before 1940, buildings with inadequate architectural configuration, lack of ductility, insufficient transversal reinforcement, highly loaded columns; the hidden damages of 1940 earthquake led to collapses of 1977 (28 high-rise buildings). Only a partial collapse of 3 buildings erected after 1960 was recorded and damages to others.

The INCERC seismic record of March 4, 1977, made with a Japanese SMAC-B, proved for the first time the spectral content of long period seismic motions of Vrancea earthquakes, the considerable duration, the large number of cycles and values of much higher accelerations than in the code, with important effects of overloading upon flexible structures. Vrancea earthquakes exceeding M_{G-R} 7 may produce a large number of cycles and overloading of weak members, especially in pre-code high-rise buildings, on large areas in Romania. In other zones, crustal earthquakes may cause damage even at lower magnitudes.

With regard to the existing building stock from in Romania, many existing buildings in urban areas are stiffer, made of masonry and concrete, but high-rise reinforced concrete structures are slender. In terms of concentration of threats, Bucharest City is a useful example. Out of the total number of buildings, over 100.000, ca. 50% represents the pre-code (1940....1950) generation, but only 300-500 of them, 0.3-0.5% of total, represents buildings higher than 6-7 stories. Some 90% of the buildings had GF….GF+1 stories and were made of masonry, stone, or local materials, with wooden or reinforced concrete floors. Pre-1940 (1944) high-rise buildings, made of gravitational reinforced concrete skeleton, made without earthquake concerns, are at highest risk.

The family of "code structures" of the period 1945-1977 includes ca. 40% of total number. The frame buildings erected until 1977 were designed at very low code forces as compared with to those considered for rigid buildings, proving lack of ductility and too large allowable drifts; many soft-story structures proved to be weak. Buildings erected after 1977 code changes reflect a new approach and safety level, while those designed after 1991, using another code, are supposed to be in a better position.

The central area of Bucharest has an agglomeration of neoclassical low-rise houses and high-rise reinforced concrete pre-1940 buildings. There are other districts with low buildings or with high-rise frame structures of 1950...1977 which can be vulnerable, as some near-to-resonance forced oscillation is a threat for flexible structures. New structures were designed to resist earthquakes. The structures made of large panels with P+4...P+8 levels have certainly the best qualities of prevention of progressive collapse.

The current architecture and urbanism relies on integrated functions with great risk exposure for large agglomerations of persons (malls, plaza, underground and over ground spaces, glass envelope, atria and other nuclei on all building height, covered canopies, external elevators etc.). New financial-banking or commercial centers, clustered in compact zones, may have a risk of chain propagation of destructive effects, not studied to date. Many structural members are sight exposed, hinged mechanical structural systems lack redundancy.

Strong winds, which were further on re-evaluated as powerful vortices or local type tornadoes, have increased their frequency and power in Romania, destroying forests, houses and networks. In August 12, 2002, a powerful storm, afterwards considered a tornado, struck village Facaieni, Ialomita County, in S-E of Romania, killing 3 persons and injuring 5. A number of 33 houses were destroyed and other 440 houses, a school and a kindergarten, the Church, were damaged. More than 1000 homeless were recorded. Other 40 railway poles and an electricity network and a forest of 120 Ha were damaged. Another tornado struck Movilita Village, Ialomita County on May 7, 2005. Some 15....24 houses remained without roofs and the church turret was thorn away, under with a wind speed evaluated at 90-100 km/h.

The safety of buildings occupants was evaluated in general terms, based on limited data on mortality and morbidity during Vrancea earthquakes, assuming an overall correlation with the vulnerability of buildings. Safety under other impacts, as interior gas explosions or storm/tornado is less documented, but large casualties were not a rule, while physical damage was mostly recorded.

Therefore, the main vulnerabilities have been identified for the high-rise buildings behaviour in earthquakes and fires. Fires have a rather constant incidence, although showing some increasing trend. Gas leaking and explosions in apartments and houses caused recently many damages. Earthquake designed structures behaved better when struck by interior explosions.

The task of providing a higher safety for structures, non-structural parts and for occupants' life will have different goals, depending on initial design patterns, importance category and age of buildings. The potential of blasts associated with urban fires following earthquakes is insufficiently studied, because until some 10-15 years ago such events were considered possible but with reduced probabilities. A part of the existing buildings, well known as being vulnerable to earthquakes and fires, can be extremely vulnerable to other extreme actions.

3. RESEARCH TOPICS IN THE PROJECT

A key problem in the multi-hazard approach is the harmonization of convergent and divergent criteria for safety requirements in case of extreme actions. For instance, loads caused by earthquakes are of short duration (tens of seconds), while those caused by explosions are of fractions of seconds. Resistance and ductility are well known as governing factors in earthquake safety design. For these types of loadings, ductility represents the main parameter to prevent collapse. Since ductility is a function of displacements and deformations, the displacement control approach is necessary for earthquakes and explosions. In case of explosions that cause impulses, the mass is important. In this respect, the concrete is an ideal material, but most recent architectural solutions include a large amount of light members, plastics, glazing, etc., prone to fire, fragmentation and projection at large distances, thus a life threat. Traditional materials, like masonry and timber may resist only to moderate blasts. Steel has definite ductility qualities, but also fire weaknesses. To solve this divergence, new studies for modelling of physical phenomena in blast and associated fires must be initiated, with specialized software, using testing and simulations, specific performance criteria and protection levels for response of structural members and personal protection in public buildings.

Although a part of principles and theoretical basis is common with that for other extreme actions, external blasts must be treated with special methods, while protective measures for constructions can be different. The behaviour of claddings at extreme actions from exterior, acting normal on their plan is less studied. Safety criteria and protection solutions for external impact are different of those required when the action is from interior, when it is necessary to provide venting, making it difficult the concerted approach.

In case of loads with a longer duration (storms), structural resistance is important. Under some critical circumstances, the risk of progressive collapse may occur, under a compound effect of impact and temperatures, shattering of debris (glass, bricks, concrete or metal chips etc), release of poisonous substances etc. all having disastrous consequences on occupants and social-economic activities.

There is a necessary link of architectural and town planning with structural engineering, to modify the traditional urban criteria, the concepts, studies and analyses on architectural shape solutions, so as to obtain safe places and increase the bearing capacity of buildings by integrated performance design.

The study of safe zone or local safe areas for protection of life at extreme actions referred to:

- safe zone / rooms for protection of life in at tornadoes (USA)
- safe zone / devices for protection of life in buildings and school classes at earthquakes (Japan, Israel)

The USA has a well known experience in civil protection and/or tornado shelters, available as guidelines and market products, more frequently used for individual houses. Concerning earthquakes, a relatively recent trend is that of special shelter-beds in Japan, to save lives in case of collapse of wooden houses. Recently, a patent of individual shelter for both earthquakes and tornadoes was presented in Romania. However, considering the patterns and weaknesses of pre-code high-rise structures, that are prone to pan-cake collapse, it is difficult to assume such a decision, instead of strengthening.

The idea of an individual shelter for students in a class, a strong desk, is already on the market in Japan. In what concerns the earthquake shelter for an entire class, in a multi-story school, a special study, design and pilot study is currently being performed in Israel by Prof. Scarlat. It refers to a class corner where a structure of steel and concrete is created to gather all class students at once and it is designed to avoid negative dynamic interaction with the main structure.

4. RESULT OF EXPERIMENTAL ACTIVITIES

The study identified the masonry as a largely highly used material for structural walls and envelope members, as solid bricks and/or hollow blocks. Concerning in-plane loading, the relevant tests to be made have been considered:

- tests on 2D frames with masonry infilling, loaded by alternate forces, or 3D masonry on shaking tables;
- tests to shear and shear with compression;
- tests on horizontal or diagonal specimens at compression.

In respect of protection solutions, a large number of advanced, composite materials, grids, plates, fabrics, polymers, laminated glass, tumescent paints etc, became available on the market and their use in new designs or in rehabilitation made possible, to prevent extreme action damages. Such technical solutions and materials already used with good results in USA, Europe and Romania have been identified, as follows:

- polymeric geo-grids as reinforcement in masonry mortar layers or as a lateral jacketing plastered with lime-cement mortar, or insert of carbon fibre rods in external nuts in mortar joints, with epoxy resins;
- carbon fibre plates or of glass fibre fabrics or carbon fibre fabrics with epoxy resins, as jacketing;
- steel bands grills, steel strands woven with polymers, with special adhesives, as jacketing;

During this project phase we used technologies and materials of international prestige, available on local market, as ISOMAT and SIKA. Some small scale laboratory testing was made in INCERC to check bond of carbon fibres on cement mortar and ceramic materials – masonry blocks using strengthening systems with composite materials: carbon fibres plates ISOMAT, Megaplate THR 3000, with adhesive Epomax-PL. The bond test at predominant shear with some tensile stress normal to the plane of shear confirmed the catalog characteristics, with a linear relationship between loading and deformation. The failure was through the concrete or through the ceramic material. The mean value of adherence - shear stress of glued plates was from ca. 1.90 N/mm^2 on flat mortar surface to ca. 2.80 N/mm^2 on ceramic blocks with a specific profile of surface.

Other INCERC laboratory tests have been made on larger masonry specimen structures, with and without protection, on diagonal specimens loaded at compression. Masonry specimens were those of standard diagonal tests, ca. 1.20 x 1.20 m and 30 cm thickness, made of Wienerberger POROTHERM clay blocks, out of which some were with a special profiling for earthquake zones. A universal testing machine of 400 tf was used, loading the specimen on its vertical diagonal until the nominal failure. During the initial test, the failure pattern followed the joints, in steps, as the adherence between blocks and mortar failed. In this state, the cracks were developed along of the mortar joint and/or through some hollow blocks, but specimens were still keeping integrity. Such a situation was considered as similar to a post-earthquake damage that deserves a strengthening, other than a wet jacketing with concrete and steel mesh.

During this project phase, we used carbon fibre plates glued with epoxy resins, having in view a comparison with previous tests without plates, on the same specimens. The strengthening systems used carbon fibres SIKA – CarboDur 1012, with adhesive Sikadur 30. In this project, 3 parallel rows of plates SIKA Carbodur 1012, with a 100 mm width and a 1.2 mm thickness were glued on masonry on both sides, on horizontal diagonals and at some height, without any other repair, then specimens were tested. During testing, the compressive force and strain on two normal directions were recorded for each step (Fig. 1).

Figure 1. The 3 specimens made of Wienerberger POROTHERM clay blocks after placing Carbon Fibre Plates Sika Carbodur S 1012 (left) and Specimen no. 1 in the testing machine at INCERC (right).

The results were as follows:

- During the test on strengthened specimen, the behaviour in the first phase reflects some adjustment of parts in contact, until the tie plates start to work, followed by the further stress redistribution between specimen and ties at higher loading. Some internal degradation of blocks, more or less visible, may have contributed to the larger deformations during the second testing.
- The positive effect of CFP ties was firstly visually recorded, as initial cracks did not advance in a destructive manner during the second test;
- As the load increased, some cracks and local failures, with slippage on mortar joints, were recorded. However, the adherence of plates to ceramic blocks surface was permanent and there was no tear-off or detachment until the end. Mentioned should be about the specifics of the block surface, with small channels that enhanced the adherence.
- The Wienerberger POROTHERM clay blocks masonry behaviour, when they were especially designed for seismic zones, proved to be advantageous, as wall thickness, profiles and keys helped the resistance;
- The specimen made of blocks that were not especially designed for seismic areas presented a larger deformation under smaller force increments, although the ultimate force was still significant.

- The nominal failure at maximum loading force was under cracking following the main stresses redistribution in the specimen. The maximum load at nominal failure, versus the initial load, ranged from 2.40 to 3.86 times. Thus, the system proved to be efficient, as a strengthening method.

A comparison with some previous similar INCERC tests on solid bricks specimens emphasized that:
- The solid brick masonry behaviour is less advantageous in terms of surfaces in contact - that are flat, both as mechanism of adherence and failure;
- A diagonal placing of plates is more efficient that the position of plates normally to masonry courses, for both the size of ultimate loads and behaviour, while the plates may suffer the detachment of their ends at failure;
- Since in some usual cases, the access cannot be provided on both sides, placing of plates at only a side can be the only solution, but it may induce the failure under a bending acting normally on the probe plane, at a load value below the one of the initial test;
- The area of carbon fibre plates in contact with blocks reached some 27% of the lateral area of a specimen. Since the blocks are higher that the usual bricks, and the mortar joints are distanced, the contact was in a greatest measure to the ceramic. As much as the solid bricks are smaller in size and thick mortar joints are more often, the contact area of clean and solid bricks ceramic material with expoxy resin and carbon fibre plates is smaller by some 15% than for blocks and thus the adherence effect is less efficient. In the case of a plastered masonry, a vigurous surface cleaning of any bricks with a wire brush is necessary.
- For any kind of masonry, when plates must be placed on both diagonals, their width and position can be changed and further studies must evaluate all aspects, including the benefits and the disadvantages, the statistical deviation of results and the cost-benefit ratio. The behaviour of key adherence areas in the frame corners, where local concentration of stresses occurs, is a topic of interest for further tests.

5. CONCLUSIONS

This project integrates concepts and requirements from architecture, urbanism and engineering for protection against natural (earthquakes, tornadoes) and man-made threats (gas explosions, terrorism), integrated in a multi-hazard approach. The preliminary study identified that in Romania there is a good theoretical and practical background for earthquake design and code enforcement. The experience for modelling and prevention of blast effects and/or other extreme impacts is not so rich. The existing built stock of Romania has suffered the impact of Vrancea earthquakes of 1940 and 1977, WW2 bombing and many fires and gas explosions and less from heavy storms, although such a threat is increasing. Large panel buildings have been especially designed by IPCT and tested by INCERC to prevent progressive collapse and showed a very good performance in 1977.

Since the recent city architecture seems more vulnerable to climatic and man-made threats, the project investigates alternatives for the strengthening of buildings, for structural and life safety. In this context, the absolute protection cannot be a goal for all buildings, but we may think to some affordable limitation of debris projection and life threatening. We need a careful analysis to see if and how the advanced materials can be used in Romania in new design and strengthening projects. For instance, the resistance of new building envelopes and their protection against impact of storm-tornado borne missiles or by external blasts is in fact unknown.

Three Wienerberger POROTHERM clay blocks masonry specimens were tested to cracking and strengthened afterwards. The maximum load at nominal failure, versus the initial load, ranged from 2.40 to 3.86 times. Thus, the system proved to be efficient, as a strengthening method. It would be expected that other tests to normal to plane loading will add knowledge. Some other solutions are related to the concept, design and use of safe-rooms. A balance of applicable solutions, between structural and non-structural parts of a building, will be studied in further phases.

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