LATERAL AND ACCIDENTAL ACTIONS RISKS OF PROGRESSIVE COLLAPSE IN HIGH–RISE BUILDINGS

Ilda Kovačević[1]
Sanin Džidić [2]

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Summary: *Progressive collapse is collapse of the whole structure or large part of it, initiated by failure of one or more structural elements or part of the structure. Such failure or damage of one structural element or part of it initiates chain reaction, comparable to domino effect and failure of other structural damages resulting in total collapse of the structure. This effect is characteristic for high–rise structures. The structure is supposed to receive and transfer all actions to the building to the load bearing soil. In majority of cases, permanent actions are predictable. Service variable loads are usually defined through national codes. However, it is not simple issue to reliably predict lateral loads, such as wind and seismic actions to the buildings. When discuss the lateral actions, their effects are major factors for high–rise structures. Lateral actions, such as wind and seismic actions increase with buildings' height and become main problem which may make building unstable, unusable, with the critical case scenario of building's collapse or over turning. The issue with accidental actions and their effects to the buildings is even more complex. Accidental actions include blasts such as explosions, detonations and bombs etc., impacts which take vehicle into consideration such as aircraft impact etc. Fire has been a main problem for construction, since the beginnings of the first more complex buildings and structures. Such accidental actions are not commonly treated and considered within structural design, so they deserve a special attention in consideration of progressive collapse of high-rise buildings as this is the case with lateral.*

Keywords: *Progressive Collapse, High-Rise Buildings, Lateral Actions, Accidental Actions*

1. INTRODUCTION

Architectural design focuses on aesthetics and functionality of designed spaces in accordance with anthropological measurements in order to satisfy users and inhabitants.

[1] Ilda Kovačević, MA in Architecture, International BURCH University Sarajevo, Faculty of Engineering and Natural Sciencies, Department of Architecture, Sarajevo, Bosnia and Herzegovina, phone: +387-61-029-886, e – mail: ilda_kovacevic@hotmail.com
[2] Prof. dr. Sanin Džidić, Associate Professor, University of Bihać, Technical Faculty and International BURCH University Sarajevo, Faculty of Engineering and Natural Sciencies, Department of Architecture, phone +387-61-905-480, e-mail: ninsa_d@hotmail.com

Following this philosophy, structures fit right into architectural design and concepts. Aplicance of this philosophy is possible due to its greatest aim in providing comfortable and rentable spaces. Structures following the architectural plans, concepts and ideas represent a common design practice in any type of buildings.
However, in the specific case of high–rise buildings, structures don't compromises on architectural design, but rather combine its advantages to preform unique aesthetic values of the high–rise volume concepts. Main responsibility of the structure is to be capable to resist failure or collapse of building under various and the critical combination of actions; meaning that the structure should have efficient performance as long as the building's service life.
Design process of high–rise buildings is important in order to provide efficient structure in resisting various actions with efficiently designed composition of structural elements which would provide rentable and functional space. Structural design should be economical in selection of structural material and required time of the erection.

2. PREDICTIBLE ACTIONS

In structural design, there are three types of design situation; persistent situation which corresponds to a normal design use, transient situation which happens during the construction phase, and accidental situation which occurs in case of earthquake or fire.

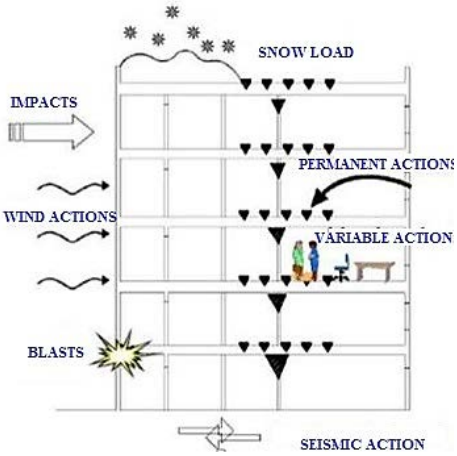

Figure 1. Types of Structural Loads on High-Rise Structure [16]

According to Eurocodes, along with these three designed situation there are also three main types of actions:

- Permanent action (K), self–weight of a structure, or so called dead loads;
- Variable action (Q), wind snow or any imposed load, including live load;
- Accidental action (A), impact from vehicle, explosion, fire etc.

Generally, no structure is designed to respond to one single action, but up to the critical possible combinations of estimated actions. Basic principles of action combinations lay in taking permanent actions in any action combination at any structure, and that each variable action is the leading action depending on building's service type. Even though limit states design in analysis takes the critical combinations of all loads and the distribution combinations, accidental actions, can cause reaching of the structure's limit state, or in other words failure of the structure. Another issue structure is dealing with is localisation of failure and prevention of progressive collapse. Progressive collapse is collapse of the whole structure or large part of it, initiated by failure of one or more structural elements or part of the structure. Such failure of one structural element or part of it initiates chain reaction, comparable to domino effect resulting in total collapse of the structure.

Few decades ago design for progressive collapse was considered only partially or was entirely neglected; however, recent happenings in the USA and Asian countries, whether discuss the attacks or gas explosion, forced more detailed structural design to prevent progressive collapses. The regulations of high–rise buildings mostly require addition of redundant members and additional tie of structural elements in order to provide more robust structures, strong, ductile and capable of redistributing accidental loads. In such design requirements new high strength and high performance materials greatly assist, whether it is the case of concrete structures or composite steel-concrete structures. Both of the mentioned materials provide more slenderness, and lighter structures with higher resistance to fire and explosions, which are main actuators of progressive collapse.

Gravity actions are permanent loads such as self-weight of structure, densities etc., variable actions – including service actions, actions during execution, various of vibrations and snow load.

Unlike any other action types, permanent action may be precisely determined and designed. Permanent actions remain constant and in the same position throughout buildings' service life, including weight of the structure and weight of the various attachments permanently attached. For the design of permanent action, it is important to have a defined type of the structural material, its density, exact sizes and weights of the structural elements derived through presumption and structural analysis.

Variable actions vary in their value and position of acting on structure. Variable actions include actions during execution, service load such as furniture, inhabitants, equipment, and others with shearing property of being movable and induced by gravity to the structure.

Variable actions, besides these occupancy weights, include traffic vibration of the vehicle movements in garages, car ramps etc., in the specific case of high–rise buildings, the accelerations of elevators has to be well calculated as type of variable action.

Practice of the Eurocodes declares specific action values for various occupancy of the buildings. For instance, National Annex to Eurocode 1, BAS EN 1991-1-1 in Bosnia and Herzegovina [49] specifies service load for residential, office, commercial, hotel and university buildings from 2 kN/m^2 for residential buildings, to 3-5 kN/m^2 in office buildings, and finally to max. 7 kN/m^2 in department stores and commercial buildings.

Different global climate conditions develop different environmental impacts and actions on structure. All of the environmental actions are considered to be variable actions due to constant change in climate conditions. Among environmental actions, snow and rain loads are the ones that are being induced by gravity to the structure. [12]

Areas with long winter season, where the snow remains for few months, require specific roof designs up to the snow load. Snow load is defined in national annexes to Eurocode 1 – Part 3, from country to country with correspondence to data of average snow amounts during the last few decades.

3. LATERAL ACTIONS

Lateral actions and their effects are major factors for high–rise structures. Lateral actions, wind and seismic actions increase with buildings' height and may make building unstable, unusable, with the critical case scenario of building's collapse or over turning. Buildings up to 10 storeys are affected by lateral actions with diminished effect. However, with buildings over ten storeys high, lateral actions become crucial in structural and architectural design. Thus, structural elements increase in cross sections, and design requires redesigning and arrangement of structural elements. At the early beginnings of high–rises in the late 19th century, wind actions and seismic actions were not focus of design, due to large, massive and stiffened structural elements and structures. However, with the development of high–strength structural materials, lighter and slenderer structures, possibility of deflection and sway became daily problem. Such situation enhanced the necessity for wind and seismic design in order to prevent collapses, loss of money, economy destruction and prevention of loss of numerous lives.
One of the most important issues of high–rise structures is wind action. Lighter, slenderer and more flexible structures are prone to sway, movement, and shake due to wind loadings. As the building's height increases, importance of wind load design increases respectively. Due to excessive heights high-rise structures are to be tested in wind tunels. Wind tunnel test actually represents behaviour of the structure's scaled model with its urban context in specific environmental loading, wind. Usually, scale is 300–400 decreased, only Burj Khalifa required scale was 1:500.

Figure 2. Burj Khalifa, Model for Wind Tunnel Testing, Scale 1:500 [18]

Ever since wind became one of the most important factors in high–rise structures, techniques, methods and approaches multiplied and different categories were discovered, which had different focuses in order to achieve better resistance to wind actions. Approaches for wind design include architectural design approach, structural design approach and mechanical design approach. [12]
Architectural design approach has its foundations in aerodynamic based designs and structure based designs. Aerodynamic architectural design is based on various factors

such as: building's position–orientation, plan variations/modifications in height, aerodynamic forms and aerodynamic tops. Each of these approaches may decrease wind effect up to 50%. Effective design, if considering building positioning or orientation at the site is prevailing wind direction, which may decrease wind effect up to 20 percent. Burj Khalifa, one of the masterpieces in aerodynamic approach to high–rise design, where successfully the building with its butterfly structure resists six types of the wind.
Plan variation is a variations in characteristic floor plans and height, and it may reflect in reduction of floor plan area or changes in geometrical shapes. In 1973, F. Khan [2] proved in his studies that at the high–rise, which has 40–storeys, and sloped facade of 8 per cent, reduced lateral drift for 50%.
Along with plan variation, aerodynamics may be developed through architectural modification, which refers to the modified rectangular in plan of high–rises, whose corners may appear to be notched, slotted, rounded, recessed etc.

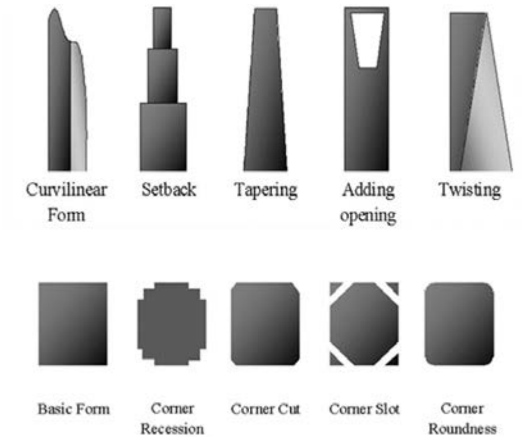

Figure 3. Schemes of Possible Aerodynamic Solutions in Architectural Forms of High–Rise Buildings Caused with Drastic Plan Variations from Floor to Floor [19]

Aerodynamic form, mostly refers to various cylindrical, conical, twisted or elliptical forms, proved to be the most efficient in reducing wind loadings. For instance, choosing circular plan form, rather than rectangular form decreases possible wind actions by 20 percent. The most common of the aerodynamic forms lays in aerodynamic top approach. Such design is based on tapering the structure's upper part, following the practice of creation of the openings in between 80 and 90 percent of buildings total height; such example may be seen in Shanghai World Financial Centre, Shanghai.
Along with aerodynamic based design, structure based design is also important for architectural design approach. In such design symmetrical, circular, elliptical and triangular plans have high structural efficiency and higher response to wind action.
Structural design should respond to resist any wind displacement which makes building undesirable and uncomfortable for use. Shear frame systems, core systems, mega frames, tubular systems, mega columns and outrigger systems are structural approaches in resisting wind.

Within mechanical design approach, engineers usually take some inherent damping in order to estimate serviceability under lateral actions, which are induced by both seismic and wind actions. The installed damper reduces wind or seismic effects.

Many territories worldwide are described as seismic zones, with different degree of seismic actions. Seismic actions are result of the buildings' dynamic response to the shaking ground. As the lateral actions increases with structure's height, seismic actions as class of lateral action behave equally. Until the mid-20th century, most of the buildings and infrastructural constructions were not adequately designed for seismic actions due to lack of technology and scientific approaches.

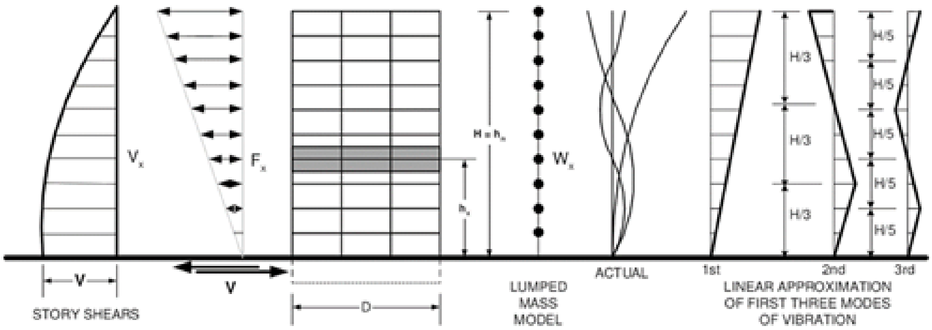

Figure 4. Diagram of Seismic Action Distribution, with Respective Increase of the Buildings Height [22]

There are evidences worldwide how even a low earthquake may cause damages or even collapse of structures. One of the latest case of progressive collapse of high–rise building due to earthquake took place in Taiwan, in February 2016, on 17–storeys high residential building.

Figure 5. Progressive Collapse of Residential 17-Storey High–Rise, caused by the Earthquake in Taiwan, February, 2016 [23]

Commonly, the main issue of collapses reflects in weak structural design and inadequately designed structures. The seismic action depends on building's mass, ground acceleration, type of foundations, structure, and load–bearing soil.

4. ACCIDENTAL ACTIONS

So far, high–rise structures, showed that accidental actions are the hardest to predict and toughest to resist if they occurs. In structural design, accidental actions refer to all possible actions which are the result of accident, impact or blast which can occur in exceptional circumstances.

Figure 6. World Trade Centre – 9/11 [24, 25, 26, 27]

Accidental actions include blasts such as explosions, detonations and bombs etc., impacts which take vehicle into consideration such as aircraft impact etc., and include fire incidents, which are the possible result of previously mentioned two load types.
Such actions are not commonly considered within structural design, but rather with variations of passive protection systems.

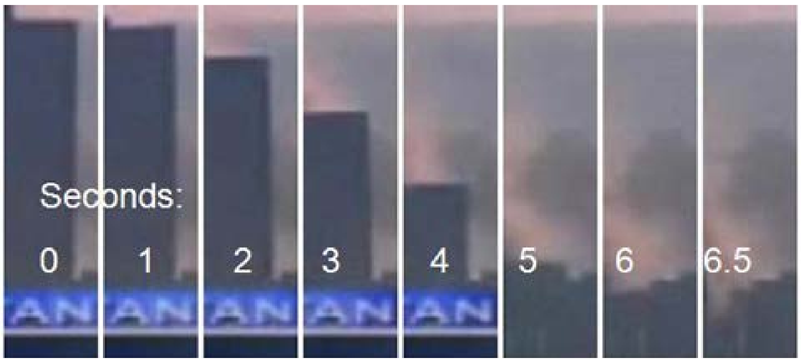

Figure 7. Progressive Collapse of the World Trade Centre in 6.5 seconds [28]

Impact happens at the moment when a body with known velocity hits structure and applies impact action and inflict a hit that causes further damages, cracking etc. When discuss the crucial impacts, those include aircraft impacts and vehicle impacts.
Figure 7 shows how an aircraft impact and bomb attack at the World Trade Centre, Manhattan, New York City, initiated fire with progressive collapse of the whole structure, where the attack did not demolish only the targets, World Trade Centre twin towers, but surrounding buildings as well.
Blasts include bomb and gas explosions, which refers to blast with condensed high explosive of hot gasses with maximal pressure of 300 kilo bars and temperature of 3000° C. Such pressure and expansion form waves with greater velocity than the velocity of sound.

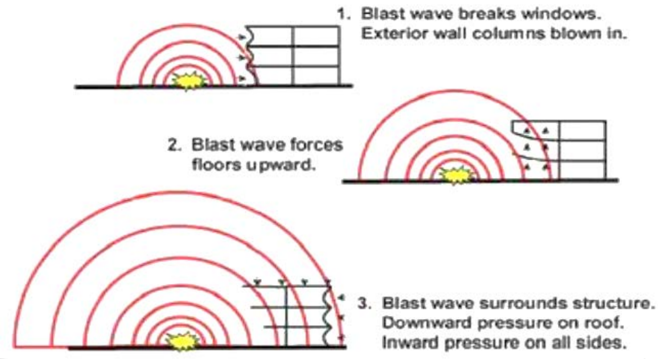

Figure 8. Exterior Blasts – Explosion next to the Building [29]

Bomb and gas explosions are difficult to take into design consideration and it is almost impossible to erect the structure which is immune to their effects and cost efficient for wider use in construction.
Gas explosions, as weaker type of blast load, generally happen due to weak and improper installation of gas pipeline in building's heating systems or mishandling of gas appliances. Even though gas explosions are localised and cause small damages, they may also initiate fire or grater damages and cracking.
Blast that initiates the worst case scenario is caused by bomb explosions which are created on purpose to injure, devastate and demolish a target. Such actions have their targets, and to design a building able to resist such power is questionable. Bomb detonations create shock waves, which expands with velocity of 1 km/s. Bomb explosions may happen next to the structure (exterior) or inside the structure (interior).
Common exterior explosion scenarios includes, broken windows and wall or column failure on the buildings' perimeter due to the pressure waves acting upon it. Floor generally falls due to large area being under excessive pressure; losing floor and beams means losing the lateral stiffness and support which indicates collapse.
On the other hand, interior explosions may be localised due to floor systems above the detonation, with load bearing walls made of concrete or masonry, which results in some local damages and possible failure of non–structural elements; however it still depends on the amount and strength of the bomb explosion.

Fire has been a main problem for construction, since the beginnings of the first more complex buildings and structures. Along with all the merits that fire enabled, there were much more damages and injuries that happened accidentally or on purpose. It is almost impossible to find a city or any urban zone, with high concentration of buildings and infrastructure that did not undergo at least partial fire expansion through city. Fire was and still is one of the greatest weapons one can have. Lately, fire became mankind's weapon with purposes to resolve disagreements; however a fire may be caused by an earthquake or any other natural disasters. [12]
World Trade Centre and many other buildings indicate that structural engineers should be more responsible for fire protection and structures' resistance to fire.

Figure 9. Mandarin Oriental Hotel, 2/9/2009, Beijing, 44 Storey, Composite Concrete and Steel Framed Structure, was Entirely Affected by Fire Remained without Structural Collapse [31, 32]

First design for fire safety were prescriptive–based designs, where the whole design was based on fire resistance of materials used in structure, while new design is based on the performance design, including evaluated strength and stiffness for a fire safety design, coupled stress–thermal analysis, specialized design for fire effects and use of fire retardants. In addition, new design for fire safety deal with advanced structural analysis in the shape of temperature–time curves, which derive structural responses during heating or cooling phases during fire.

5. CONCLUSION

Ever since lateral actions became one of the most important factors in high–rise structures, but techniques, methods and approaches multiplied and different categories were discovered, which had different focuses in order to achieve better resistance to lateral actions. Approaches for wind design include architectural design approach, structural design approach and mechanical design approach, while the seismic action depends on building's mass, ground acceleration, type of foundations, structure, and also load–bearing soil. However, these issues can be successfully resolved by proper selection of structural systems and construction materials.

The greatest challenge in high–rise structures are accidental actions are the hardest to predict and toughest to resist if they occurs. In structural design, accidental actions refer to all possible actions which are the result of accident, impact or blast which can occur in exceptional circumstances. Future research in modeling of accidental actions generally, but specifically to high-rise constructions are mandatory tasks for engineering community. And accidents happen!

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ПОПРЕЧНА И ИНЦИДЕНТНА ДЕЈСТВА – РИЗИЦИ ПРОГРЕСИВНОГ КОЛАПСА КОД ВИСОКИХ ЗГРАДА

Резиме: *Прогресивни колапс представља отказивање цијеле конструкције или њеног дијела, који је инциран отказивањем једног или више елемената конструкције или дијела конструкције. Такво отказивање или оштећење једног елемента конструкције може узроковати ланчану реакцију упоредиву са домино ефектом, која може довести до оштећења других елемената носиве конструкције, а тиме и до рушења цијеле конструкције. Ова појава је карактеристична за високе зграде. Задатак конструкције објекта је да прими сва аплицирана дејства и да их пренесе до носивог тла. У већини случајева, стална дејства на конструкцију су предвидива. Употребна промјенљива дејства се дефинишу националним прописима. Међутим, није лаган задатак да се поуздано одреде попречна дјеловања на конструкцију, као што су дејства вјетра и сеизмичка дејства. Ова попречна дејства представљају важна и незаобилазна дејства у разматрању носивости и стабилности високих зграда с обзиром да се повећавају са висином објекта, те могу угрозити носивост и стабилност објекта или чак довести до његовог рушења. Питање дјеловања инцидентних дејстава на конструкцију представља још комплекснији проблем. У инцидентна дејства спадају експлозије, али и удари возила и летјелица на конструкцију, као и пожари који представлају проблем за конструцкије још од првих комплексних објеката и конструкција. Инцидентна дјеловања на конструкције се не разматрају уобичајено у конструктерском пројектовању, тако да она заслужују посебну пажњу у разматрању прогресивног колапса високих зграда, као што је случај са попречним дјеловањима*.

Кључне речи: *Прогресивни колапс, Високе зграде, Попречна дејства, Инцидентна дејства*