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REVIEW OF BUILDING DESIGN SYSTEMS AND PROBLEMATIC STRUCTURAL ELEMENTS INHIBITING PROGRESSIVE COLLAPSE

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ABSTRACT: To design for blast or ballistic loadings a structure is or has been subjected to, a designer needs to be fully aware of all aspects of normal building design systems that will be confronted as well how the mechanism of collapse will or has occurred. Some structures, depending on how they are designed or constructed, possess inherent structural problems that can impede collapse. In the case of a controlled demolition (implosion) prior to the use of explosives RC stairwells should be removed, RC facia with windows removed, all internal cladding and ceilings removed and internal shear walls used to accommodate wind loadings demolished. RC floors should be weakened by removal of sections of the concrete floor matric thus allowing for the formation of plastic hinges when the tensile forces in the floors shift to the reinforcing steel causing it to yield. Everything possible must be done to facilitate collapse and allow gravity to assist in the process. With an uncontrolled demolition (implosion) many factors are unknown during the design process and assumptions must be made. In this case based on past events, explosives and charge weights used must be assumed in advance of an event but nevertheless the design engineer must produce a design that facilitates a delay in collapse long enough for those caught inside the structure to escape to safety. Understanding building design systems in relation to possible collapse and problematic structural elements that could possibly inhibit such collapse are imperatives in designing for and against explosive demolitions.

Keywords: Implosion, Building Systems, Progressive Collapse, Problematic Elements

1. INTRODUCTION

The main causes of structural damage to a building not only occurs as a direct result of the blast and ballistic loading to the building but also the collapse of the building and fragmentation [1] caused by the attack or loose fragments picked up in the path of the blast and fire.

2. TYPICAL BUILDING DESIGN SYSTEMS

FEMA 453 Risk Management Series “Safe Rooms and Shelters – Protecting People against Terrorist Attacks” [2] provides figures of typical buildings systems that could well be subjected to blast and ballistic loadings as guidance for architects and designers to arrive at better designs that will minimize damage by understanding the systems [3] that will have to withstand such loadings [4]. Structural building systems in multi-storey high-rise buildings are designed to cater for vertical gravity loads and lateral loads caused by wind or seismic activity [5]. The structural system consists effectively only of the members designed to carry the loads whilst all other members are being referred to as non-structural members.

2.1 Tensile Structures

Members of tensile structures [6] are subjected to pure tension under the action of external loads. Because the tensile stress is uniformly distributed over the cross-sectional area of members all material within such a structure is used in the most efficient manner.

2.2 Compressive Structures

Compression structures [7] develop mainly compressive stresses under the action of axial loads. Because compressive structures are susceptible to buckling or instability the possibility of such a failure should be considered in their designs if necessary and adequate bracing should be provided to avoid any failures.

2.3 Trusses

Trusses are composed of straight members connected at their ends by hinged connections [8] to form a stable configuration. Because of their light weight and high strength, they are amongst the most commonly used type of structures.

2.4 Shear Structures

These are structures such as reinforced concrete shear walls that are provided in multi-storey buildings to reduce lateral movements due to wind loads and earthquake displacements [9]. Shear structures develop mainly in-plane shear with relatively small bending stresses under the action of external loads.

2.5 Flexural Structures

Flexural structures develop mainly flexural stresses under the action of external loads such as with blast loadings [1]. The shear stresses associated with the changes in bending moments are significant and should be addressed in any such designs.

2.6 Load Bearing Walls

A structural wall carries the weight of any building system from the roof and upper floors down to the foundation [10] with the weight at any point in the structure being the load being transferred.

2.7 Steel Moment Frames

Modern high-rise buildings and many mid- and low-rise buildings rely on steel moment frames to resist lateral loads [11] arising from winds or earthquakes. Lateral loads imposed on a building caused by wind are externally applied but lateral loads from earthquakes result from internal inertial loads that develop because of the ground displacement and so leading to the building's foundation accelerating forward. Steel moment frames consist of beams and columns joined by a combination of welding and bolting. They resist lateral loads through the bending of the frame elements. In the case of wind loads and moderate earthquakes loadings, steel frames designed using current building codes are intended to remain elastic. In other words when the loading ceases all the steel beams and columns constituting the frame are expected to return to their original position without any permanent deformation

2.8 Shear Walls

A shear wall is a structural system composed of braced panels (also known as shear panels) to counter the effects of lateral load [11] acting on a structure. Wind and seismic loads are the most common loads that shear walls are designed to carry.

2.9 Flexible Diaphragms

When considering the P-Delta and buckling behavior of multi-storey buildings [12] consideration should be given to modelling the floors as flexible diaphragms when they are connected to walls that carry vertical loads. This allows tensile membrane forces to develop within these flexible diaphragms which may be necessary to balance the compressive forces that result where floors resist the horizontal Poisson expansion of vertically loaded walls. Without this balance between forces the P-delta effect [13] reduces the torsional stiffness of the wall system possibly causing excessively large torsional deformations, elongated torsional periods, low buckling factors, or convergence problems for P-delta analysis.

2.10 Rigid Diaphragms

When walls are subjected to vertical compressive loading, horizontal Poisson expansion occurs [14]. In a structure, adjoining slabs resist this horizontal expansion thus causing compressive horizontal stresses within the walls and tensile stresses in the slabs. The compressive stresses within the walls reduce the torsional stiffness of the structure whereas the tensile stresses in the slabs balance this effect by increasing the torsional stiffness. However, when diaphragm constraints are assigned to slabs these tensile forces do not develop since rigid diaphragms are constrained against in-plane deformation. When wall systems carry gravity load interconnecting slabs should be modelled as flexible diaphragms such that membrane behaviour balances the compressive effect of horizontal Poisson expansion.

2.11 Gravity Load Frames

In this case frames consisting of columns and beams carry the gravity loading for the structure [11]. Reflecting on the above, all types of structures high-lighted and the structural elements incorporated within these buildings can be clearly identified in all building systems.

3. PROBLEMATIC STRUCTURAL ELEMENTS

Fig.1 to 8 highlight several problematic structural elements (Fig.7) [15] that need to be addressed prior to a controlled demolition (implosion) being carried out. If they are not addressed the progressive collapse can be inhibited and so total collapse will not be achieved and so this means that safety is compromised. In the case of jointed precast structures (Fig. 2) once explosives are detonated their collapse occurs very quickly necessitating large safety distances are in place for blasters and the viewing public. Flat slab column floor connections (Fig.3) need to be addressed using substantial explosive charge weights to weaken the connections and so allow collapse not to be hindered. In the case of post tensioning systems (Fig.4 & 5), they need to be severed with linear steel cutting charges to allow the building to freely collapse without interfering in the trajectory of the fall. Steel riveted structural elements (Fig.6) present a problem as they normally shear when subjected to blast loadings possibly leading to unwanted fragmentation which then adds to safety issues. Composite steel and concrete structures (Fig.8) cause problems with controlled demolitions as substantial preparatory work to be undertaken prior to demolition. Lastly, dust control (Fig.1) is important as cementitious particles are like asbestos particles and so if inhaled they can cause lung cancer. Whether the control is via the application of water spray of some form of water-based polymer spray local authorities will mandate that dust suppression must be included in the design of a controlled explosive demolition.

Fig.1 RC structures produce a cementitious dust cloud (9-11 Research.com 9 September 2015)

Fig.2 Jointed Precast Structures Collapse Quick (FIB Bulletin No 43 May 2003)

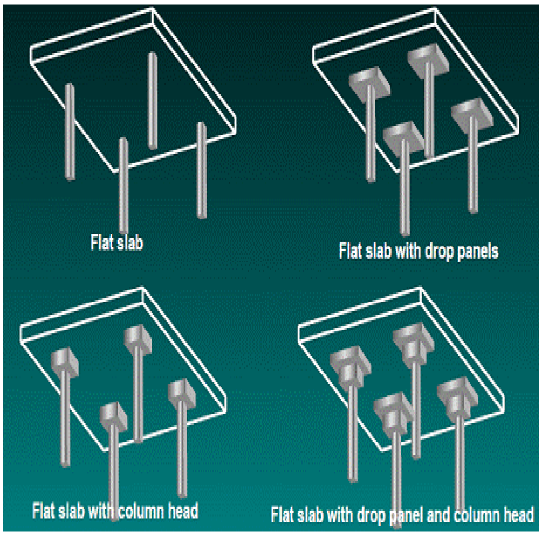

Fig.3 Flat slab column floor connections (Quora 18 June 2015)

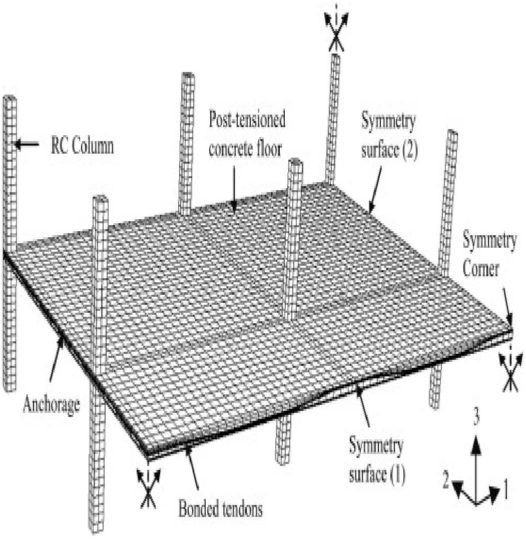

Fig.4 Typical post tensioned floor and RC column (Building Construction 30 April 2017)

Fig.5 Bonded and un-bonded multi-strand post tensioning system (VSL Systems 2017)

Fig.6 Riveted structures first to collapse through shear (CanStock Riveted Joints 17 July 2012)

Fig.7 Cast in-place type structures where pre-preparation is critical (A4Architects.Nairobi 23 July 2014)

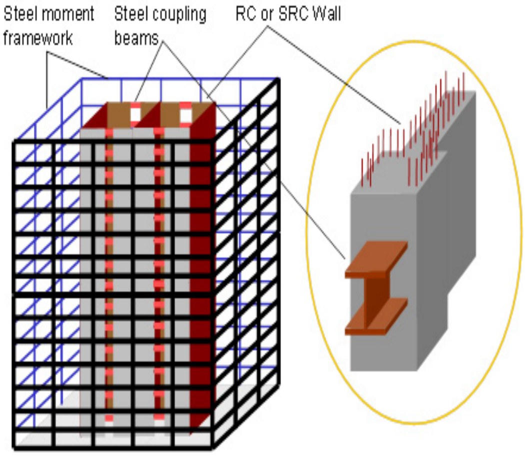

Fig.8 Composite steel and concrete structures cause problems (Sterchelegroup Building Systems)

4. COLLAPSE

Apart from damage any designer is obliged to design against progressive collapse [16] or at worst delay through a specific design process any progressive collapse occurring. The following structural features can be applied to any design to prevent the spread of damage throughout a structure because of one of the initiating events.

4.1 Redundancy

The provision of redundant load paths in a vertical load carrying building system [17] ensures that alternate load paths are available in the event of the local failure of structural elements to provide for adjoining structural elements to carry these new loads.

4.2 Ties

The loss of a major structural element typically results in load redistributions and member deflections. These processes require the transfer of loads throughout the structure (vertically and horizontally) through alternate load paths [11]. The ability of a structure to re-distribute or transfer loads along these load paths is based on the interconnectivity between adjacent members [18]. Fig.9 illustrates the different types of ties that are typically incorporated to provide structural integrity to a building

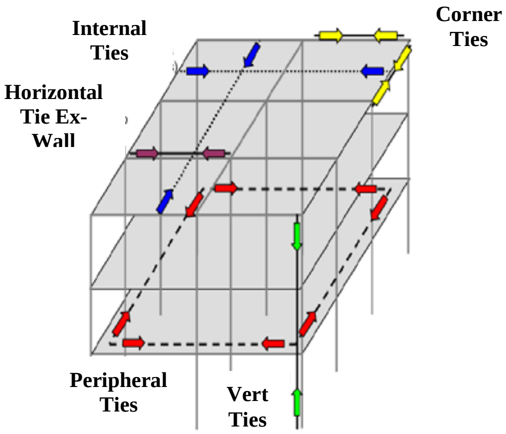

Fig.9 Different types of ties incorporated to provide structural integrity (FEMA 453)

4.3 Ductility

In a catastrophic event, members and their connections may have to maintain their strength through large deformations [19] (deflections and rotations) and load redistributions associated with the loss of key structural elements. For reinforced concrete and reinforced masonry structures, ductility is achieved by providing sufficient confinement of reinforcing steel [20], providing continuity in reinforcement through adequate lap splices or mechanical couplers, maintaining overall structural stability and creating connections between elements that exceed the strength and toughness of the base members.

4.4 Adequate shear strength

Structural elements in vulnerable locations like perimeter beams or slabs need to be designed to withstand shear load [21] more than that associated with the ultimate bending moment in the event of loss of an element. Direct shear failure is a brittle mode of failure and should not be the controlling failure mechanism whereas shear capacity should always exceed flexural capacity to encourage a ductile response. Typical two-way slabs without beams [22] must provide post failure resistance in the presence of punching shear failures and severe distress around the columns.

5. CAPACITY FOR RESISTING LOAD REVERSALS

The primary structural elements such as columns, girders, roof beams and lateral load resisting systems coupled with secondary structural elements such as floor beams and slabs should be designed to resist reversals [23] in load direction at vulnerable locations.

6. FRAME STRUCTURES

In frame structures column spacing should be limited as large column spacing decreases the ability of the structure to redistribute loads [24] in the event of column failure through blast loadings. In the case of the loss of a transfer girder or a column supporting a transfer girder this will inevitably lead to the destabilization of a large area of the building. Transfer girders at the building exterior often are designed to accommodate large column beam spacing thus increasing their vulnerability to blast loadings. At best, it is far more desirable to adopt designs that don’t require transfer girders or at worst add redundant transfer systems where transfer girders are required. In bearing wall systems that rely primarily on interior cross-walls interior longitudinal walls should be spaced periodically to enhance stability and so control the lateral progression of damage [25]. A bearing wall system is a combination of primarily either horizontal members or structures and vertical wall structures that are designed to transmit applied loads to the ground. In such bearing wall systems that rely on exterior walls or perpendicular walls substantial rectangular columns projecting out from a wall should be provided at a regular spacing to control the amount of wall that is likely to be affected by a blast loading. Resistance to progressive collapse [26] can be achieved by providing extra strength to connections. Numerous connections will permit for a more uniform smooth load redistribution and prevent sudden changes in strength and stiffness that will result in load concentration, overstress and early failure. For a concrete frame structure, there are design options that can be provided to raise resistance to progressive collapse and they include the use of moment resisting connections in beam-column joints [27] that will sustain load reversals and simple load connections are necessary for ordinary construction.

7. CONCLUSIONS

FEMA 453 May 2006 Risk Management Series Safe Rooms and Shelters [2] provides a detailed graphical list of building structural systems to assist designers in designing not only against blast loadings in new buildings but also in existing buildings that may be needed to be retrofitted to withstand certain design loadings. The structures cover all building materials such as wood, reinforced concrete, masonry and steel. Such building systems whether single storey or multi-storey may have to be designed for both controlled and uncontrolled demolitions to mitigate against damage and delay progressive collapse. The key during any design process is to understand those structural elements that are susceptible to blast and ballistic loadings within the buildings and structural systems and so design these structural elements to be able better accommodate blast loadings. The aim being always to mitigate against the level of damage and to stop collapse at best but delay where possible. Fig.10 is a damage assessment flowchart showing that it is necessary to understand the explosive involved and its charge weight (kg) before attempting to assess any likely damage outcome. Nevertheless, it is also necessary to know whether the building concerned has or has not been designed to withstand blast or ballistic loadings. In advance this means that the designer has a reasonable idea as to whether the damage outcome will be minimum or substantial. This information helps with an explosive demolition and so achieving a safe and successful outcome.

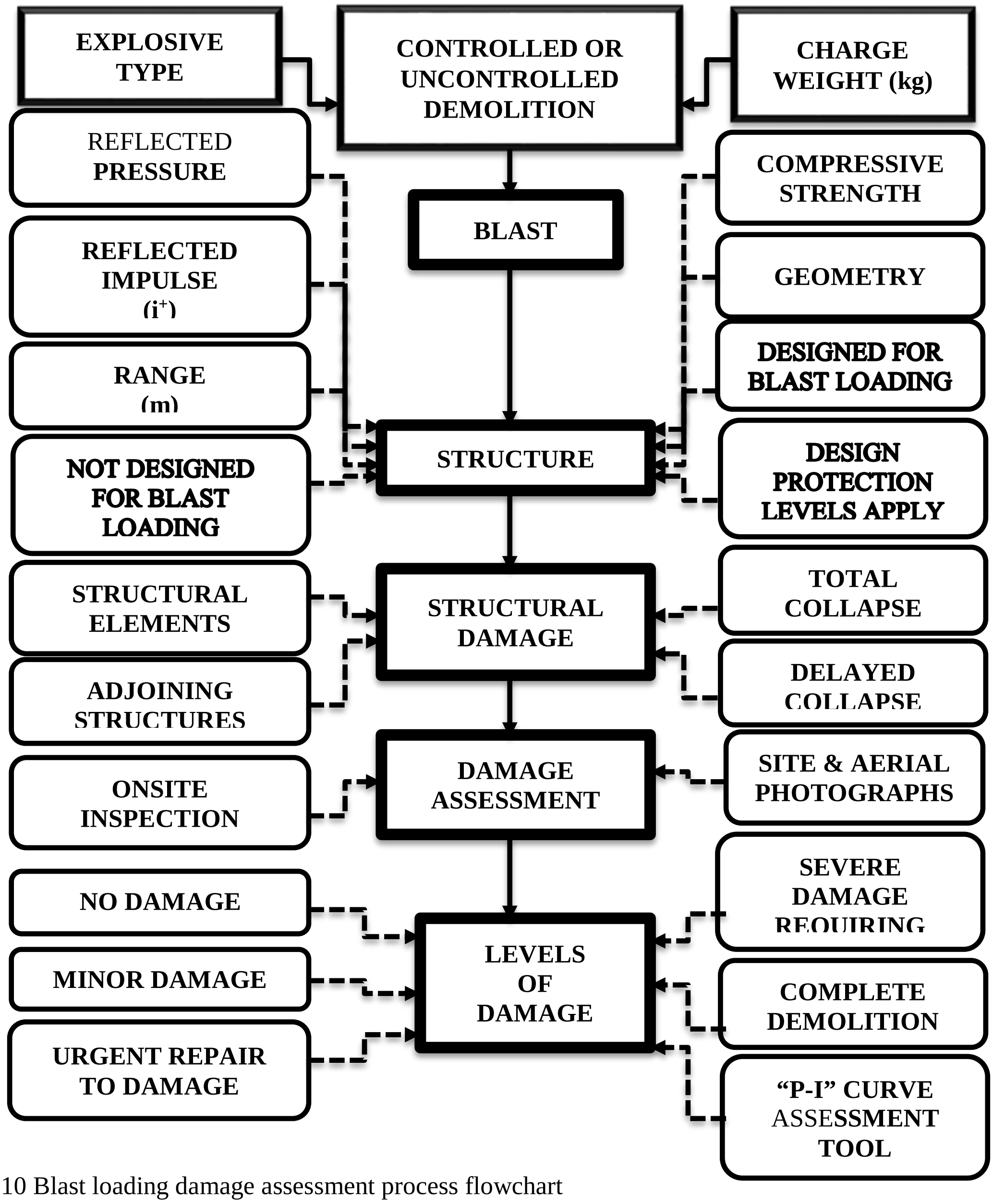

Fig.10 Blast loading damage assessment process flowchart

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