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Progressive Collapse Mitigation in Flat-Slab Buildings

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Abstract

This paper discusses challenges and proposes solutions in relation to progressive collapse mitigation in flat slab systems. Traditional flat slab floor systems gained increased popularity in many parts of the world as a result of the ease of construction which translates into construction cost saving. However, flat slab floor systems are particularly vulnerable to progressive collapse if appropriate precautions are not taken during the design. Design approaches addressed in this paper include; alternate path (AP), tie force (TF), and enhanced local resistance (ELR).
This paper advocates the use of an effective system of reinforcement ties that has the ability to develop catenary action in flat slabs and transfer the redistributed forces through vertical members to the ground.

Keywords: progressive collapse, catenary action, structural ties, punching shear, flat slab.

1 Introduction

Flat slab floor systems gained increased popularity in many parts of the world due to ease of construction which translates into construction cost saving. This was the case in the United Arab Emirates during the boom of the construction industry in the past decade. However, flat slab floor systems are particularly vulnerable to progressive collapse if appropriate precautions are not taken during design. For example, punching shear stresses may trigger progressive collapse. Magnitudes of punching shear stresses will increase during a progressive event leading to exacerbation of the event and delay in reaching a state of stable equilibrium.
For all floor systems, solutions to mitigate the effect of progressive collapse should have limited or no interference with architectural functionality. The demand for larger open spaces is particularly critical for flat slab construction. Furthermore, structural design that inhibits progressive collapse is not practical for most structures

intended for civilian use. This paper advocates the design of an effective system of reinforcement ties that is capable of developing catenary action in flat slabs and transferring redistributed forces to the foundation. The lack of stiffness in flat slab systems caused by the relatively small thickness of the slabs represents a challenge in employing the AP approach for progressive collapse mitigation.

2 Strategies for Mitigation of Progressive Collapse

Design requirements for mitigation of progressive collapse in UFC [1] are related to the Occupancy Category of the structure. The AP design approach is required for occupancy categories III, and IV and optional for occupancy category II.
Provision of tie forces is optional for Occupancy Category II but mandatory for Occupancy Category IV. ELR is optional for Occupancy Category II and required for Occupancy Category III and IV.

Progressive collapse in flat-slab and flat plate structures may be initiated by the failure or damage of primary load-carrying vertical member. Event is more critical if the vertical member is located at the ground level. Progressive may also be initiated in flat slab construction due gravity-driven failure at slab/column connection known as punching shear. In either case, the strategy to mitigate progressive collapse generally falls under either or both of the following two categories:

- Design and construction measures to reduce of the potential for the trigger of progressive collapse. Example of these measures include:
    - Enhanced local resistance (ELR) for corner and penultimate columns.
    - Provision of adequate punching shear capacity.
- Design measures to maintain integrity of the structure after an event triggers failure that may lead to progressive collapse. Examples of these measures include:
    - Provision of structural ties as described in Chapter of 3 of UFC [1].
    - Employing the AP approach to design of structural elements.

The lack of flexural stiffness in flat slabs when applying the AP approach is discussed in section 2.1. The advantage of providing mechanically spliced continuous structural ties to develop catenary action is discussed in section 2.2.

2.1 AP Approach and Lack of Stiffness in Flat Slab Systems

The AP approach requires the design of the structure to have the ability sustain the loss of primary load-carrying member without overall collapse of the structural system. This involves removal of essential primary load carrying members at prescribed locations. If elastic analysis is used, the structure should have the stiffness to sustain the loss of these primary elements.

A typical flat slab floor may have thickness in the range of 18 cm to 25 cm. This small slab thickness leads to a structural system that may not have the stiffness to bridge over a removed column as required by the AP approach. Unlike slab-beam systems, tensile membrane or catenary action is of primary interest and can be developed in flat slab systems.

2.2 Mitigation of Progressive Collapse after a Triggering Event – Focus on Structural Ties

Provision of a system of horizontal and vertical ties represents one of the indirect approaches for progressive collapse mitigation. Tie-forces must be developed to maintain minimum structural integrity after initiation of failure. Tie forces associated with collapse are provided by reinforcement bars, structural members, and/or special detailing. Maintaining structural integrity in post-failure situations may save lives.

Following the initiation of flat slab failure, it is more reasonable to count on the tensile resistance of the system. Provision of appropriate reinforcement ties leads to tensile forces which develops catenary action in slab. For tensile stresses and the associated catenary action to develop:

- Continuous load path for membrane forces in slabs must be provided to transfer load to adjacent supports.

- Proper restraint must be provided at the supports to resist the additional pull imposed by the damaged slab.

Reinforcement bars should be mechanically spliced to ensure continuity and reliability of the reinforcement load path. It was shown that concrete has little influence on the post-failure behaviour and the development of catenary action [3].

2.2.1 Double Reinforcement Not Over-reinforcement

If a vertical column supporting flat slab/plate floor is severely damaged, the slab may not have ability to span over the removed member as required in the AP method. This is due to the relatively small depth of the slab compared to beams in slab-beam system. Therefore, the author recommends that the AP method not be used for flat slabs when spans are relatively long. Instead, catenary action developed by structural ties in flat slab should be relied on to maintain structural integrity after damage.

Structural ties in horizontal plane of flat-slab/plate construction or slab-beam system should be part of the original reinforcement system needed to resist traditional design loads. The following tie reinforcement should be provided:

- Column strip top reinforcement that are designed for the original loads, must be provided in two orthogonal directions and checked for UFC [1] progressive collapse loads.

- Reinforcement bars designated as ties should be mechanically spliced continuously from end to end of the slab.
- Reinforcement equal to that at the top of the column strip must be placed at the bottom and be mechanically spliced.
- Reinforcement ties in the column strip on top and bottom must be anchored to peripheral ties.

The suggested top and bottom tie reinforcement layout is shown in Figure 1. It is identical the recommendation of UFC [1], except for the proposal in this paper to concentrate tie reinforcement in column strip areas. If calculated reinforcement ties are more than the original column strip reinforcement, then the additional reinforcement ties must be distributed in the column strip.

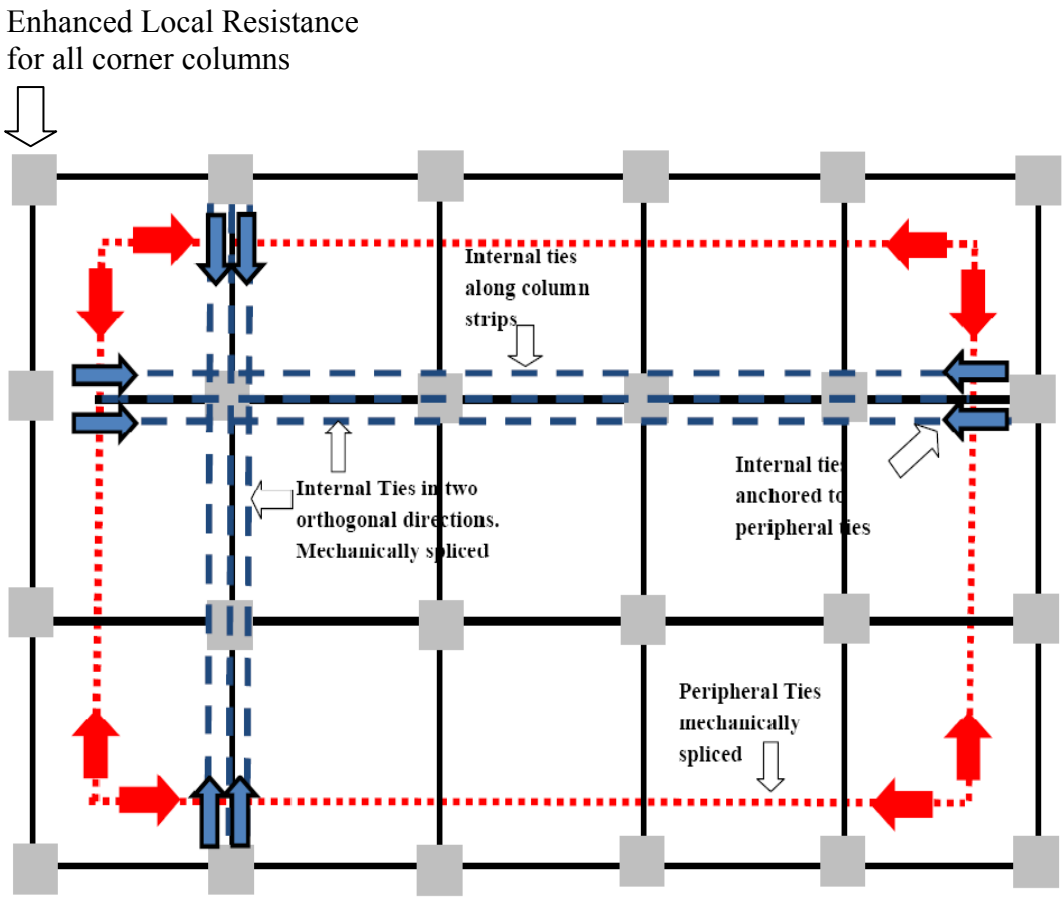

Figure 1: Internal and peripheral ties in flat slab construction

Mechanically spliced and continuous bottom reinforcement at column strip can help mitigate progressive collapse in two ways:

- If punching shear occurs, bottom reinforcement will provide a secondary mechanism and vertical shear resistance at the slab/support joint to support

the slab after the initial shear failure. This was observed by Moehle [6]. Figure 2 demonstrates how mechanically spliced bottom reinforcement would provide vertical shear resistance in post-failure situations, thereby, maintaining structural integrity.

- If a vertical support is damaged and can no longer support the slab, stress reversal will occur and may be resisted by the bottom reinforcement in the column strip.

If properly designed, bottom reinforcement and/or top reinforcement ties will develop the desirable catenary action.

Excessive reinforcement added to serve as ties could result in over-reinforcement, which is generally undesirable for traditional strength design method.

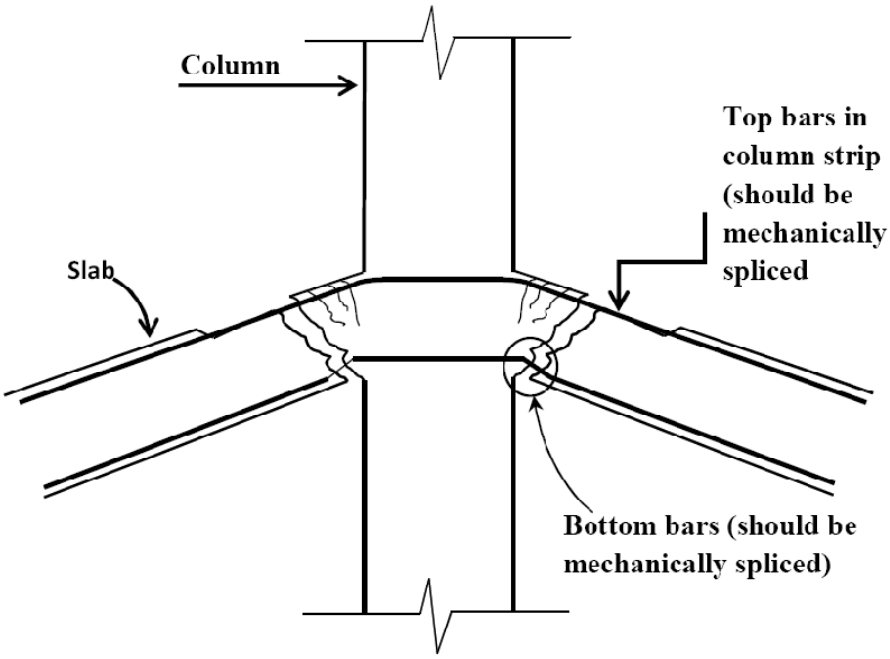

Figure 2: Bottom reinforcement in column strip resisting shear

The load path of tensile forces in the horizontal plane must continue to vertical load carrying members. The primary consideration is that vertical members must have tensile capacity to carry the pull imposed in them to the foundation. Figure 3 demonstrates that all vertical members must be able to provide continuous load path to the foundation as demonstrated in UFC[1].

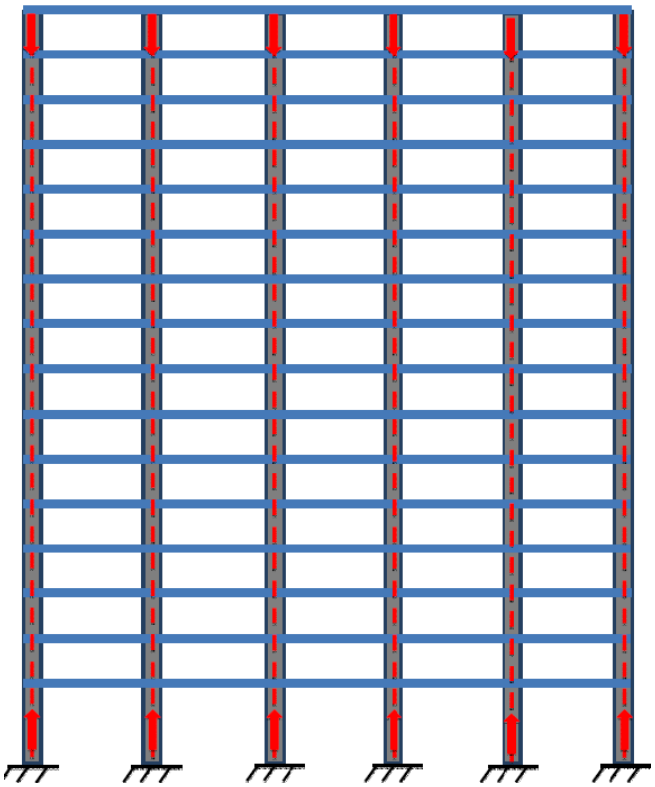

Figure 3: Vertical tie reinforcement in an elevation view

2.2.2 Design of Tie Forces in Flat Slab and Flat Plates

The three types of reinforcement ties generally used to provide ductility and integrity in the post-failure are:

- In-plane: These horizontal ties include internal longitudinal and transverse in addition to peripheral ties.

- Vertical ties: Running vertically along column and wall lines.

UFC [1] requires design of structural ties using traditional Load and Resistance Factor (LRFD) equation.

$$\emptyset R_n \geq \sum \gamma_i \, Q_i \qquad (1)$$

$\emptyset$ = strength reduction factor
R_n = nominal tie strength
γ_i = load factors
Q_i = load effects
Q_i: Load effect

Progressive collapse is gravity driven. Gravity load combination used to calculate the load effect Q_i is:

$$W_F = 1.2D + 0.5L \quad (2)$$

W_F = Combined gravity load (kN/m^2)
D = Dead load (kN/m^2)
L = Live load (kN/m^2)

2.2.3 In-plane Ties

Internal Ties

As discussed earlier, longitudinal and transverse ties are typically placed in two orthogonal directions in floor and roof slabs.
The current UFC [1] recommends calculating required strength of internal ties, F_i (kN/m) according to equation (3).

$$F_i = 3W_F L_1 \quad (3)$$

Where,
F_i = Required tie force, per unit width, in the direction into consideration (longitudinal or transverse)
W_F = Floor load (kN/m^2)
L_1 = Greater distance between centrelines of support lines of spaces in the direction into consideration (longitudinal or transverse)

Peripheral Ties

The required strength F_i (kN) for peripheral ties, in the longitudinal or transverse direction is:

$$F_i = 6W_F L_1 L_p \quad (4)$$

L_1 = 0.91 m

Floors and roof system are used to carry the required peripheral tie strength. If beams, girders, or spandrels are present, they may be used instead of the floor/roof system, if they are capable of carrying the peripheral tie force while undergoing an 11.3-degree rotation.
Peripheral ties must be placed within 0.9 meter of the edge of a floor or roof. If perimeter beams, girders, or spandrels are present, the 0.9 meter distance is measured from the interior edge of the beam, girder or spandrel.

2.3 Mitigation of Potential for Progressive Collapse – Focus on Punching Shear Capacity

Localized punching shear in flat slab could trigger progressive collapse. Therefore, special emphasis should be given to design of column-slab connection to resist punching shear and avoid triggering of progressive collapse. ACI 318 [3] includes provisions for design against punching shear.

In flat-slab construction, if progressive collapse is initiated by a reason other than punching shear, such as loss of primary vertical load carrying member, availability of proper system of structural ties may allow tensile forces to maintain structural integrity while the floor system develop catenary action, as explained in section 2.2.

If catenary action develops due failure triggered by reasons other than punching shear, excessive deformation may still cause punching shear failure to occur, as discussed by Regan [2]. The recommended bottom tie reinforcement in the column strip area will provide vertical shear resistance.

Figure 4 shows the deformed shape of flat slab structure after loss of a primary vertical member. Stress reversal that occurs at the location of the damaged support requires the presence of mechanically spliced bottom reinforcement to transfer the loads to the adjacent columns. At slab/column connection, punching shear could occur due to transfer of moments and shear. Once again, bottom reinforcement that is mechanically spliced will help maintain structural integrity.

2.4 Mitigation of Progressive Collapse – Enhanced Local Resistance for Corner Columns

The recommendations on previous sections on development of catenary action relates to loss of vertical support members that are either internal or external, but not at the corner. Catenary action cannot be developed at corner panels after the loss of a corner column/wall. A comprehensive mitigation strategy calls for protecting corner columns through ELR approach. Discussion on corner panels of corner buildings can be found in Mohamed [4,5].

3 Future Research Needs

Tie forces must be calculated in order to design structural ties. As discussed in the previous section, empirical formulas were provided by the UFC [3] to calculate in-plane tie forces as well as vertical ties. There is a need conduct nonlinear cracked section analysis for the floor slab to provide a better estimate of the tie forces for in-plane forces as well as vertical support elements. For this type of analysis, gravity load combinations must include dynamic effects.

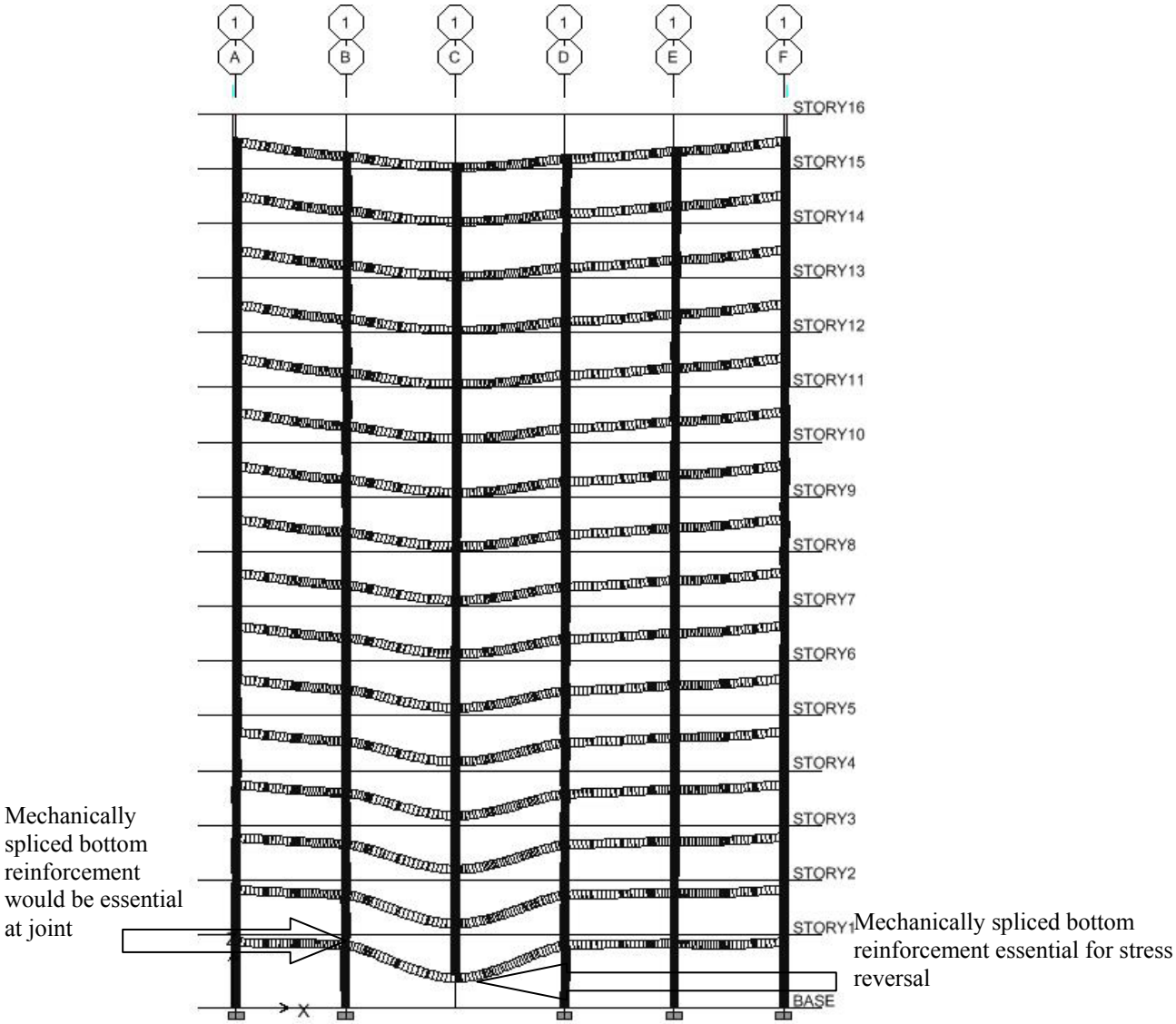

Figure 4: Flat slab deformation after loss of primary support

4 Summary

Performance of flat slab buildings under progressive collapse situations can be improved by properly designing and detailing the slab to develop catenary tensile strength. This may be done by an appropriate orthogonal grid of mechanically tied reinforcement bars placed on top and bottom in column strips. In such case, if a flat slab structure is damaged, integrity would still be maintained to allow evacuation and rescue activities. Bottom reinforcement bars in a column-strip that are mechanically spliced and anchored at peripheral ties that provide vertical shear support are column-slab joints.

Special attention should be paid to design and detailing of the slab-column joint to guard against punching shear, which could trigger progressive collapse. The UFC [1] provides empirical formulas for the estimation of the magnitude of the design forces for horizontal internal and peripheral ties. However, further research is needed to provide accurate estimates of forces that are necessary to develop catenary action in the post-failure situations. This should include loads that account for the dynamic effects of falling debris.

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