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Optimum Geometry of Steel Diagrid Structural System to Resist Progressive Collapse

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Abstract: This paper focused on applying progressive collapse (PC) procedures on a diagrid system structure and performing an optimization process to find the optimum angle to mitigate the PC with consuming minimum steel weight. The study is performed by analyzing 36, 48, and 60-storey diagrid systems with different inclination angles, 50.2º, 67.4º, 74.5º, and 82.1º, with 2, 4, 6, and 12-storey modules, respectively. This study relied upon the sudden load-bearing element loss technique using the alternative load pass method described by the UFC09 code [1], by using ETABS software [2]. The analysis results show that the optimum inclination angles range between 75° to 82°. .

Keywords: **:** Progressive collapse, Diagrid system, Finite element, Alternate load path method**,** Optimization.

1. INTRODUCTION

The commonly used structural systems of high-rise buildings are the rigid frame, shear wall, dual rigid frame, and shear wall, braced tube system, hexa-grid system, tube-in-tube system, bundled tube system, core-and-outrigger with belt truss, and staggered truss system [3, 4, 5].

Diagrid is a structural system that allows all vertical columns to be removed, leaving just triangular-shaped formed inclined columns on the building's façade creating a unique view for the building. This technique allows more sunlight to penetrate the building throughout the induced open façade. The main components of the diagrid system are the inclined brace-shaped members connected to ring beams at diagrid nodes arranged every few floors forming diagrid modules as shown in Fig.1 [6].

The application of exterior diagonals improves the aesthetics of the building which in turn attracted the attention of architectural and structural designers of tall buildings. The main difference between the braced tube structure and the diagrid system is that vertical columns are removed from the perimeter of the diagrid building as shown in Fig.2 [7].

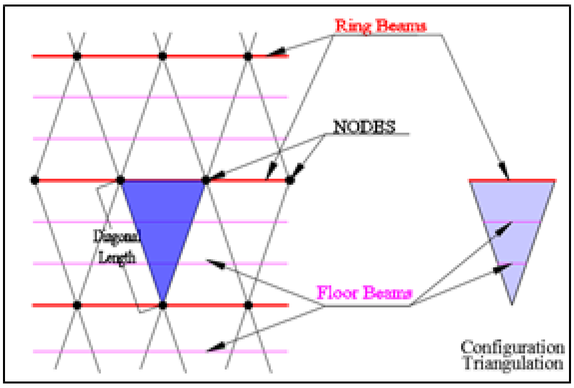
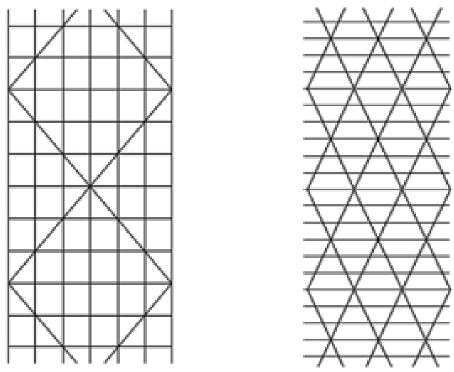


FIG 1. Components of a diagrid system Asadi et al., 2018 [6]



(a) Braced tube **(b)** Diagrid structure
Fig2. Braced tube vs. diagrid system Moon et al., 2007 [7]

The diagonals carry both gravity loads and lateral forces as they play as inclined columns and also as a bracing system; due to their triangular pattern, internal axial forces are mainly induced in the members which decrease shear racking effects [8]. An early application of the diagrid system in Pittsburgh was the IBM building constructed in the early 1960s, Hearst Tower (New York), Capital Gate (Abu Dhabi), CCTV headquarters building (Beijing), West Tower (Guangzhou), Mode Gakuen Spiral Tower (Aichi), The Swiss Re tower (London), etc. [3].

Several studies were performed on the diagrid system to investigate its behavior and enhance its strength. Moon et al. (2007) [7] presented a stiffness-based method for determining preliminary member sizes of steel diagrid structures, the accuracy of this methodology was verified by SAP2000 [9] results. Yadav and V. Garg [8] studied the advantages of the diagrid system compared to other conventional structural systems. Asadi et al. [6] studied the behavior of steel diagrid structures against seismic loading and performed a complete investigation on the nonlinear performance of diagrid systems using static, time-history dynamic, and incremental dynamic analyses. Tomei et al. [10] proposed a new design method that depends on sizing optimization to improve the preliminary design method to deal with complex and non-conventional patterns of diagrid structures. Devansh et al. [3] performed a parametric study on diagrid structures against earthquake loads by changing parameters such as diagrid angle, cross-sectional shape, and column location. Results of maximum top storey displacement, storey drift, and base shear were compared. It was found that the corner column location was the most efficient, the best section was the I section, and the optimum angle was 63 degrees. M. Vhanmane and M. Bhanuse [4] studied the performance of the diagrid system for high-rise steel buildings by changing the number of stories with different diagrid arrangements, modeling, and analysis were carried out by ETABS [2] software. They found suitable diagrid angles for different heights. They also performed a comparison with conventional structures in terms of floor displacement, storey shear, inter-storey drift, steel weight, and stiffness. They concluded that the diagrid system produces better performance than the conventional system without considering progressive collapse (PC).

Previous researchers focused on determining the optimal configuration of the diagrid structure grid geometry to resist gravity and lateral loads. It is important to take progressive collapse prevention into account while designing and analyzing modern structures. Progressive collapse (PC) is defined as the spread of an initial local failure from one element to adjacent elements resulting eventually in the collapse of an entire structure or large part of it [1, 11]. PC can be triggered by a variety of causes, including design, construction errors, gas explosions, bomb detonations, and vehicular collisions [12]. Recent building codes give guidelines and recommendations that should be followed and respected to enable structures to resist progressive collapse, among them, GSA (2003) [13], and UFC 4-023-03 (2009) [1]. Yara et al. [14] performed a parametric study using nonlinear dynamic analyses to study the progressive collapse resistance capacity of steel moment-resisting frames and braced frames. The alternate path method was followed as recommended in UFC guidelines.

Finally, few researchers applied PC procedures on diagrid structure systems using UFC 4-023-03 (2009) [1] provisions and studied their behavior. The objective of this paper is to investigate the effect of the inclination of the diagonal angle on the potential of the diagrid system to resist progressive collapse.

2.PROGRESSIVE COLLAPSE CODES PROVISIONS AND PROCEDURES.

The Unified Facilities Criteria (UFC 4-023-03, 2009) [1] provides the design requirements necessary to minimize the potential of progressive collapse for existing and new structures. The linear static procedure (LSP) is performed on structures to carry out the UFC09 alternate load path method of analysis (ALPM). This method is used to check the capability of the structure to bridge over the deficient element after it has been notionally removed [1]. Two removal scenarios are applied to load-bearing elements, the first is when one pair of diagonals on the perimeter middle is removed and the second is when one pair of diagrids on the corner is removed. Locations of removed braces are at ground level. Each removal scenario is applied one at a time. Two separate models are used to verify the acceptance of structural components throughout deformation-controlled and force-controlled actions. It is important to know how these methods differ widely in load combinations, material properties, and acceptance criteria.

In general, structure elements' response according to ductility can be considered as deformation-controlled action if they are allowed to exceed their elastic limit in a ductile behavior, and considered as force-controlled demands when they are not allowed to go beyond their elastic limits, described as brittle or non-ductile. Two types of load combinations are defined in this clause. Equation (1) and Equation (2) are applied to those bays adjacent to the removed diagonals for deformation-controlled and force-controlled models, respectively. Equation (3) applied to the rest of the bays as per Equations (3-10), (3-11), and (3-12) in UFC09.

$$G_{LD} = \Omega_{LD}\,(1.2D+0.5L) = (1.2D+0.5L)\ 1.98D_{in}+0.825L_{in}) + LAT \quad (1)$$

$$G_{LF} = \Omega_{LF}\,(1.2D+0.5L) = (1.2D+0.5L) + (1.2D_{in}+0.5L_{in}) + LAT \quad (2)$$

$$G_{LD} = G_{LF} = (1.2D+0.5L) + LAT \quad (3)$$

Where G_{LD} and G_{LF} are the factored loads for LSP of deformation-controlled actions and forced-controlled action, respectively. D_{in} and L_{in} are the increased dead load and live load due to column removal, respectively. LAT is the lateral loads.

Ω_{LD} and Ω_{LF} are the load increase factors that take dynamic and nonlinear effects into consideration after sudden load-bearing removal for deformation-controlled and forced-controlled action, respectively. For steel frames, "Ω_L" is calculated according to Equations (4-a & b).

$$\Omega_L = \begin{cases} \Omega_{LF} = 2 & \text{for force-controlled load combination.} \quad (4\text{-a}) \\ \Omega_{LD} = 0.9m_{min} + 1.1 & \text{for deformation-controlled load combination.} \quad (4\text{-b}) \end{cases}$$

The factor m_{min} is the smallest m of any primary beam, girder, or spandrel directly connected to the removed column within the area of the structure that is immediately affected and that help to resist progressive collapse, excluding columns. The demand modifier (m) is a factor taken to consider the expected ductility at a specific structural performance level [15], m factors for each element and connection are defined in Table 5-1 in UFC09 and Table 5-5 in FEMA-356 (2000) [15]. For steel members, m-factors are calculated as a function of member compactness for flexure members and a function of both member compactness and axial stress for axially loaded members. In the current study, the smallest m-factor is calculated according to the load increase factor Ω_{LD} is equal to 2.65 for deformation-controlled load combinations.

$$m_{min}=(2.3 - 0.021d) \quad (5)$$

where d is the depth of the beam, inch.

The lateral load is applied perpendicular to the structure faces one each time according to Equation (6).

$$LAT = 0.002\Sigma P \quad (6)$$

Where ΣP is the Sum of the gravity loads (Dead and Live) acting on only that floor without load increase factors [1,16]. Note that gravity load and lateral load combinations are merged. so, there are 4 load combinations for each lateral load for one column removed at one time.

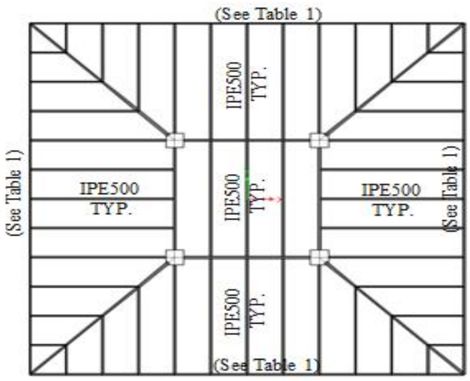


Fig 3. Plan for used beam sections.

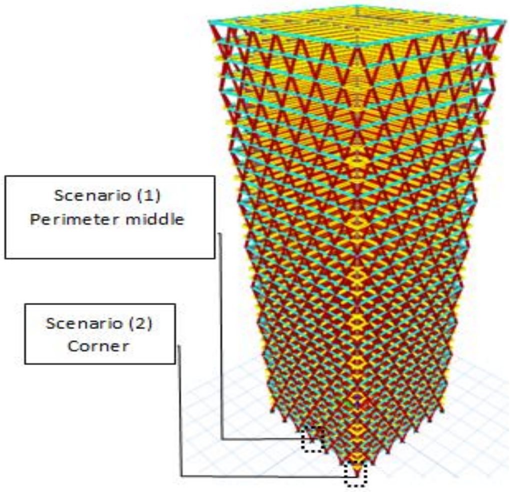


Fig 4. Three-dimensional model.

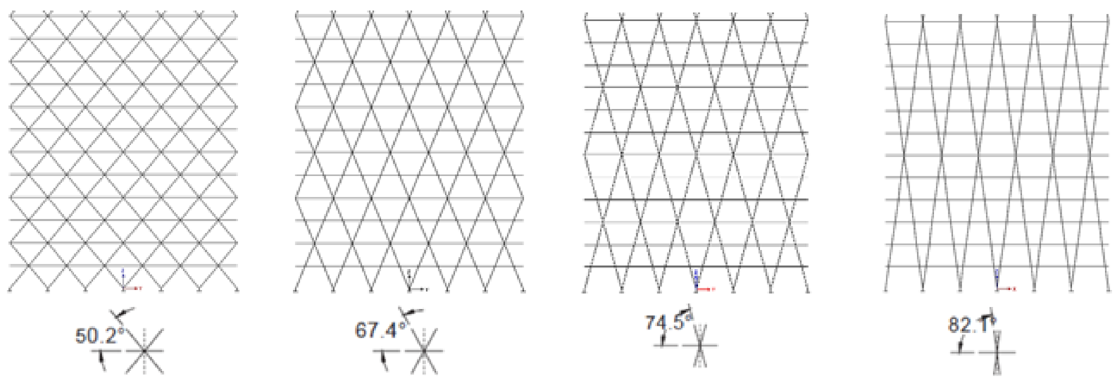


Fig 5. Various diagonals configuration

4. RESULTS AND DISCUSSION

Analysis results are presented in terms of top storey displacement, inter-story drift, storey shear, and percentage of increase in structure weight for different configurations.

4.1 Storey displacement

Fig.6, Fig.7, and Fig.8 show storey displacement due to scenario (1) removal for 36, 48, and 60 storey, respectively under gravity and lateral X. direction loading. Fig.9, Fig.10, and Fig.11 show story displacement due to scenario (2) removal.

Fig.12 and Fig.13 present the top storey displacement for different inclination angles of studied heights for scenario 1 and scenario 2 removal, respectively considering the same section properties and loading. It is observed that the diagrid system's optimum angle that leads to minimum storey displacement ranges from 75º to 82º.

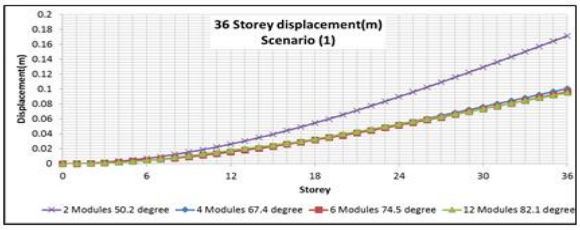


Fig 6. Story displacement due to scenario (1) removal for 36-story structure.

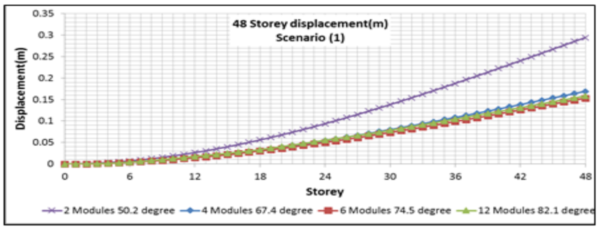


Fig 7. Storey displacement due to scenario (1) removal for 48-storey structure.

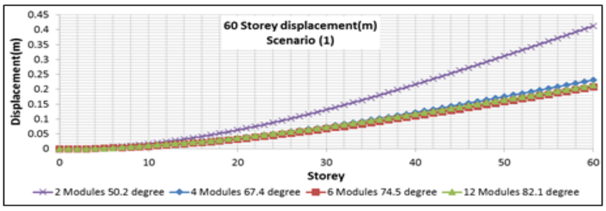


Fig 8. Storey displacement due to scenario (1) removal for 60-storey structure.

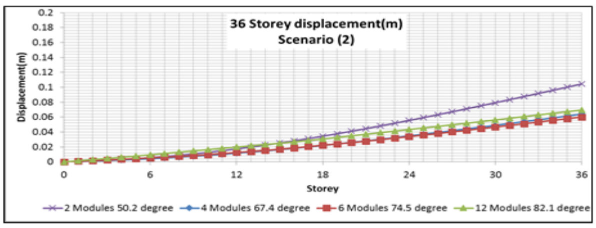


FIG 10. Storey displacement due to scenario (2) removal for 48-storey structure.

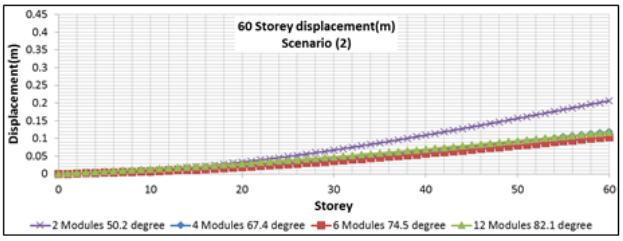


Fig 11. Storey displacement due to scenario (2) removal for 60-storey structure.

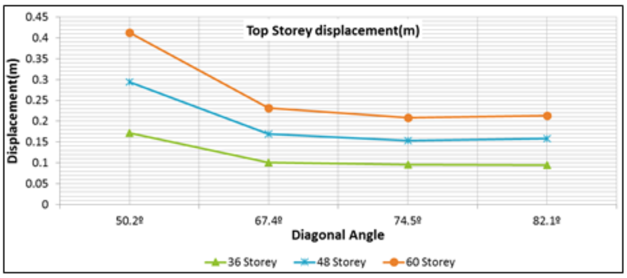


Fig 12. Top Storey displacement of 36, 48, and 60-storey structures due to scenario (1) removal for different diagonal angles.

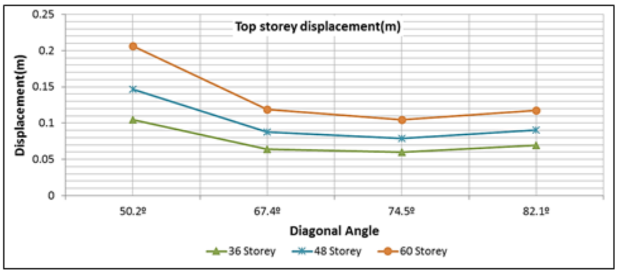


Fig 13. Top Storey displacement of 36, 48, and 60-storey structures due to scenario (2) removal for different diagonal angles.

4.2 Inter storey drift

Inter-storey drift due to scenario (1) for different heights is presented in Fig.14 to Fig.16 and scenario (2) removal is presented in Fig.17 to Fig.19.

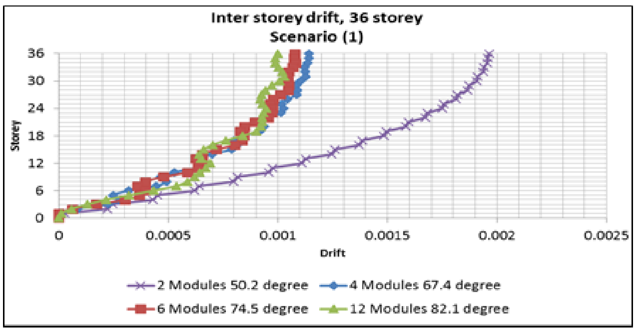


Fig 14. Inter storey drift of 36-story structure, scenario (1) removal

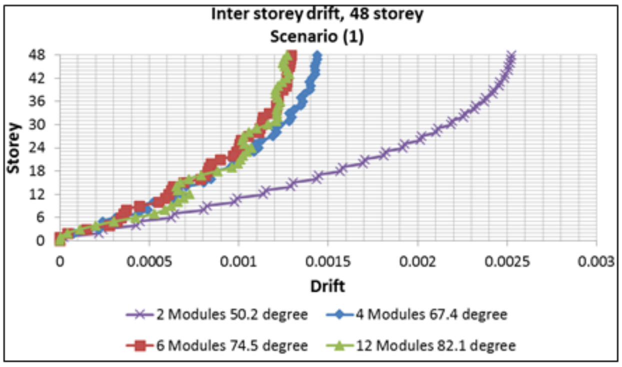


Fig 15. Inter storey drift of 48-storey structure, scenario (1) removal.

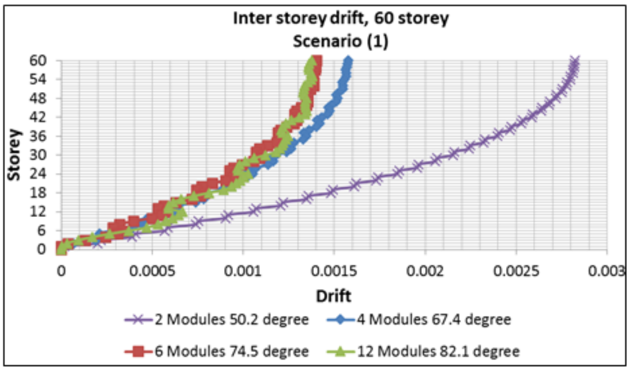


Fig 16. Inter storey drift of 60-storey structure, scenario (1) removal.

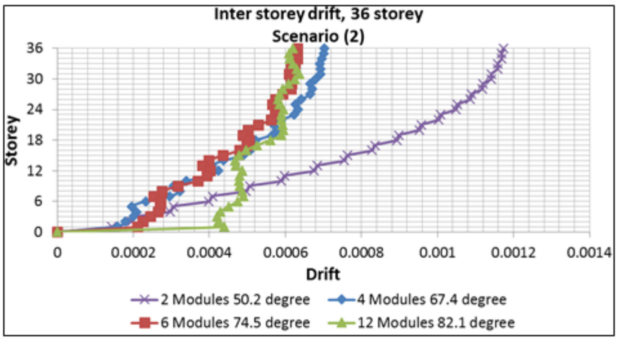


Fig 17. Inter storey drift of 36-story structure, scenario (2) removal.

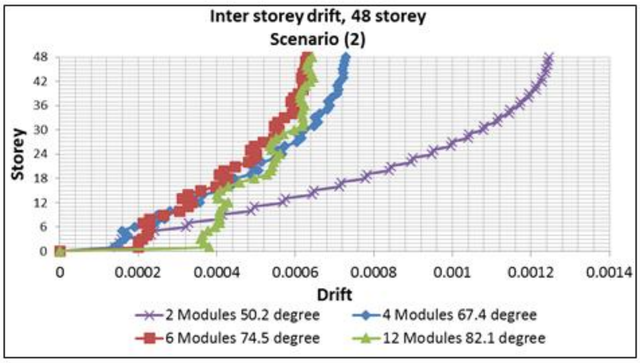


Fig 18. Inter-storey drift of 48-storey structure, scenario (2) removal.

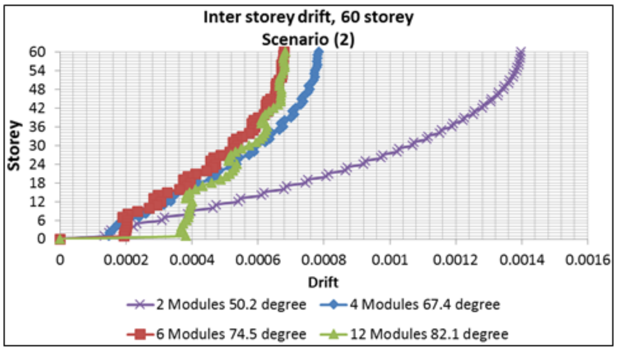


Fig 19. Inter storey drift of 60-storey structure, scenario (2) removal

The comparison of the inter-story drift results between different configurations of the diagrid system is performed as seen in Figure 20 for scenario 1 removal and Figure 21 for scenario 2 removal. This means that a diagrid angle of 75° to 82° is suitable for 36, 48, and 60-story building structures.

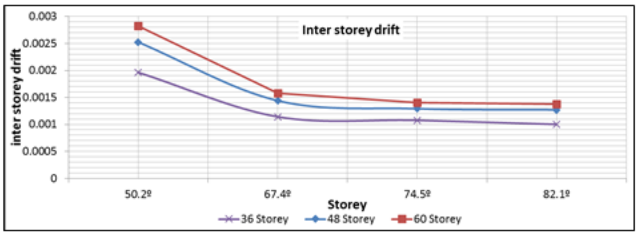


Fig 20. Inter-storey drift at the top level of 36, 48, and 60-story structures due to

scenario (1) removal for different diagonal angles.

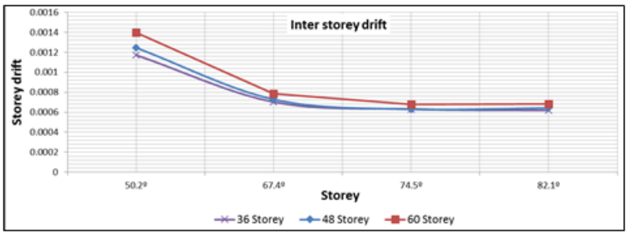


Fig21. Inter-story drift at the top level of 36, 48, and 60-story structures due to

scenario (2) removal for different diagonal angles.

- **Storey shear.**

Storey shear is uniform for all configurations as presented in Fig.22 and Fig.23 for scenarios (1) and (2) removals, respectively of 36-storey structure.

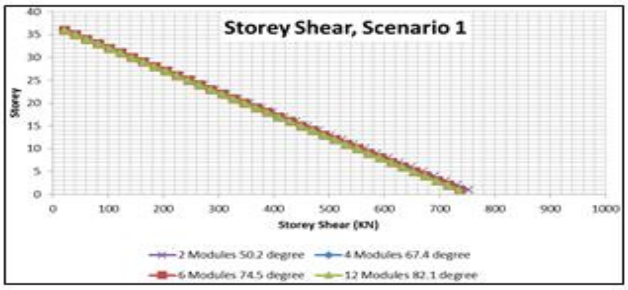


Fig22. Storey shear, scenario (1) removal

Fig 23. Storey shear, scenario (2) removal

4.4 Structural weight for removal scenarios.

Minimizing the structure weight is the most concerning outcome of the optimization procedure. As the core elements are not affected by the PC, the weight of the perimeter elements for different configurations and different heights is determined from ETABS models as summarized in Table.1 and Table.2 for scenarios (1) and (2) removal, respectively. Fig.24 shows the perimeter elements weight of different structural configurations for the 36, 48, and 60 srorey structures for scenarios (1) removal and Fig.25 for scenarios (2) removal.

TABLE 1.: Perimeter Diagonals and beams weight for different stories and different configurations due to scenario (1) removal.

No. of stories	Inclination Angle	Diagonal Section	Perimeter Beam Section		Weight of Perimeter beams + diagonals (Ton)
			Intermediate	Cantilever	
36	50.2°	CHS 450X50	IPE 360	IPE 500	4304
	67.4°	CHS 450X40	IPE 360	IPE 500	3036
	74.5°	CHS 450X40	IPE 360	IPE 500	2921
	82.1°	CHS 450X42	IPE 500	IPE 500	3126
48	50.2°	CHS 650X50	IPE 360	IPE 500	8401
	67.4°	CHS 650X35	IPE 360	IPE 500	5183
	74.5°	CHS 650X34	IPE 360	IPE 500	4868
	82.1°	CHS 650X38	IPE 600	IPE 500	5629
60	50.2°	CHS 900X55	IPE 360	IPE 500	15984
	67.4°	CHS 900X33	IPE 360	IPE 500	8442
	74.5°	CHS 900X30	IPE 360	IPE 500	7443
	82.1°	CHS 900X38	IPE 600	IPE 500	9975

TABLE 2.: Perimeter Diagonals and beams weight for different stories and different configurations due to scenario (2) removal.

No. of stories	Inclination Angle	Diagonal Section	Perimeter Beam Section		Weight of Perimeter beams + diagonals (Ton)
			Intermediate	Cantilever	
36	50.2°	CHS 450X75	IPE 360	IPE 550	5933
	67.4°	CHS 450X49	IPE 360	IPE 550	3582
	74.5°	CHS 450X45	IPE 360	IPE 550	3218
	82.1°	CHS 450X44	IPE 500	IPE 550	3245
48	50.2°	CHS 650X75	IPE 360	IPE 550	11904
	67.4°	CHS 650X45	IPE 360	IPE 550	6454
	74.5°	CHS 650X42	IPE 360	IPE 550	5842
	82.1°	CHS 650X43	IPE 600	IPE 550	6637
60	50.2°	CHS 900X83	IPE 360	IPE 550	23095
	67.4°	CHS 900X45	IPE 360	IPE 550	11184
	74.5°	CHS 900X41	IPE 360	IPE 550	9873
	82.1°	CHS 900X41	IPE 600	IPE 550	10621

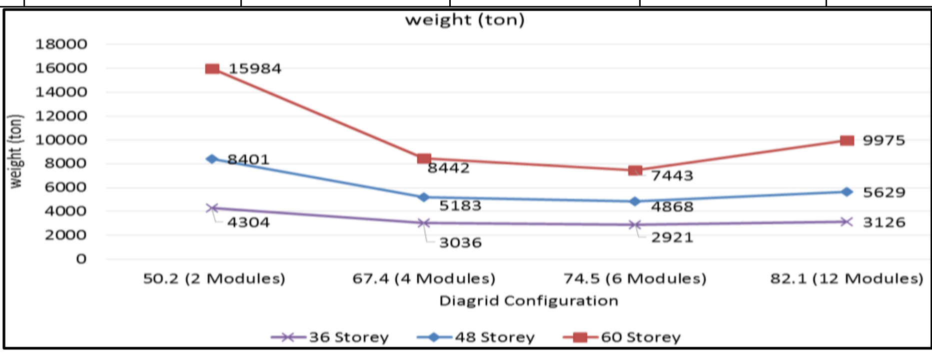


Fig 24. Structure weight for different diagonal angles of 36, 48, and 60-storey structure due to scenario (1) removal.

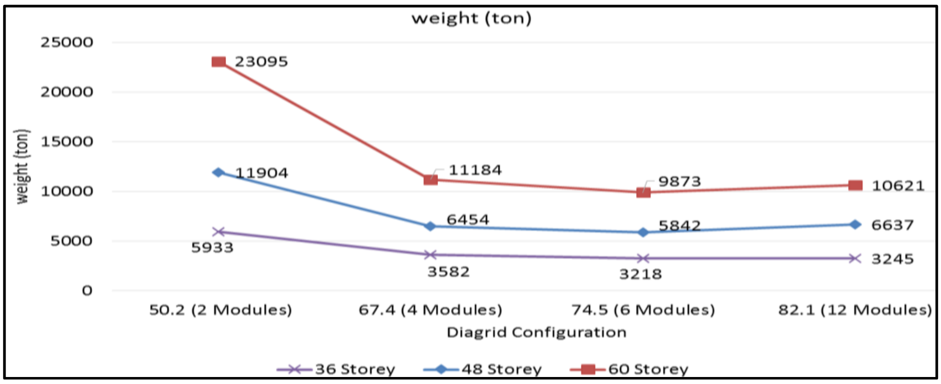
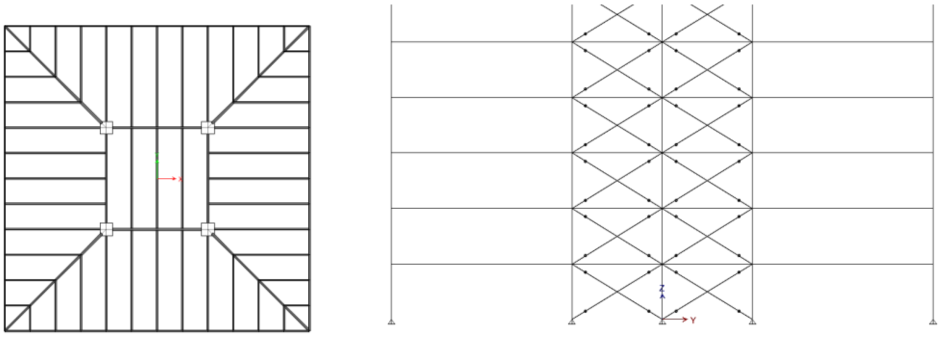


Fig 25. Structure weight for different diagonal angles of 36, 48, and 60-storey structure due to scenario (2) removal.

TABLE 3. : Weights (ton) for different configurations of diagrid system and Conventional columns/bracing system

Inclination Angle	Weight of Perimeter beams + diagonals (Ton)	Conventional columns/bracing system (Ton)	% of difference
50.2º	4304	4336	0.75%
67.4º	3036		30%
74.5º	2927		32%
82.1º	3126		28%



(a) Plan (b) Elevation

Fig 26. Elevation and plan of conventional columns with the bracing system

It is previously observed that the optimum angle ranges from 75° to 80° which can be identified more precisely after comparing the structure weight of the examined models. The optimum angle is 75° as it consumes less tonnage of steel. For 36 storey building, in scenario (1) removal, the structure with a diagonal angle of 82° requires an increase in steel weight by +7% to that of 75° and +0.83% in the case of scenario (2) removal. Percentage of difference in weight between angles 75° and 82° increases when the number of stories increases. For the 60-storey building, in scenario (1) removal, the structure with a diagonal angle of 82° requires an increase in steel weight by +34% to that of 75° and +7.58% in the case of scenario (2) removal.

An interesting comparison can be performed considering the weights of different diagonal angles of the diagrid system with the conventional columns/bracing system as shown in Fig.26. In the 36-storey structure, the conventional system requires 32% more steel tonnage than the diagrid system in the case of angle 75°, this ratio decreases as the inclination angle decreases which reaches 0.75% for diagonal angle 50.2º as shown in Table.3.

5.CONCLUSION

This paper presents the effect of the inclination angle of diagonals on the progressive collapse (PC) mitigation of diagrid structures against (PC). Four different configurations of 36, 48, and 60 storey heights are investigated to identify the most effective and economical way to increase the PC resisting capacity. The alternate load path method analysis outlined in UFC09 is applied by conducting two removal scenarios: the first is when one pair of diagonals on the perimeter middle is removed and the second is when one pair of braces on the corner. The parameters of storey displacement, inter-storey drift, and storey shear are studied. To obtain a rational design, all models are redesigned to compare the weight of the structure.

Based on finite element results, it can be concluded that, for all investigated building heights, the diagrid structure generally has high resistance to progressive collapse caused by the sudden loss of perimeter diagonals when the diagrid angle is between 75° to 82°. A diagrid angle in the range of 75° to 82° provides less top-storey displacement and the lowest inter-storey drift which reflects more stiffness to the diagrid system for this range. Changing diagonal angles has a small effect on the results of storey shear. It could also be concluded that angle 75° is the cost-effective angle as it consumes less tonnage of steel. Finally, the diagrid system is more economical than conventional columns with a bracing system.

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