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PERFORMANCE-BASED SEISMIC STUDY FOR GLOBAL VS LOCAL FAILURE OF VERTICALLY IRREGULAR RC STRUCTURES

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Abstract: The significance of local damages in the seismic performance of vertically irregular Reinforced Concrete (RC) building structures was emphasized in post-earthquake damage reconnaissance studies, forcing earthquake engineers to focus on reducing the destructive effects of earthquakes on buildings. This matter is of increased significance especially when it comes to structures having deficiencies in the lateral resisting systems, as these irregularities will have a detrimental impact on the structure's behavior. Non-linear analysis has been undertaken to investigate the seismic performance of RC Moment Resisting Frame (MRF) buildings with vertical irregularities in the form of transfer storey. Case study buildings were assessed using (FEMA-356, 2000) standards. Global Inter-storey Drift Ratio (IDR) limits were compared to their counterparts that are based on member-level criteria, for the prediction of the unfavorable soft-storey mechanism. Under various variables, correlations have been developed to assess different structure's predicted seismic behavior. In this study, member-level criteria (local damages) were employed to forecast the afore-mentioned local failures and then compared to global-level criteria to not only understand the behavior but also give the key criteria and limitations that should be investigated for these kinds of structures.

Index Terms **– Seismic performance, RC MRF, Soft-storey, Transfer storey, Performance levels, Inter-storey drift, Member-level criteria, Global-level criteria.**

1. INTRODUCTION

Seismic design methods have been developed over time far more than any other load situations, such as gravity, wind, and snow. Because the geology of an earthquake is difficult to duplicate in a lab, many issues remain unsolved, and nature continues to be the primary laboratory. Building performance after severe earthquakes invariably exposes faults in design and construction practices, necessitating correction. As our understanding of earthquake occurrence and ground motion characteristics has grown, scientists have been able to replace empirical principles with scientifically grounded ones. The evolution of computer-aided design tools and analytical methods has influenced a paradigm change in design practices.

To this day, the seismic designs of not only the most common, but also the most complex buildings are carried out using the Force-Based Design (FBD) method. While this strategy is conceptually clear and thus appealing, it is now known that most code FBD approaches are based on several imperfect concepts, and these imperfections can potentially lead to non-conservatism.

Even though earthquakes impose deformations on buildings rather than forces, seismic design has traditionally followed a force-based design (FBD) process as an extension to conventional gravity and wind load design techniques. According to extensive research and empirical evidence, designing a structure to respond in the elastic range to a ground motion representative of a maximum intensity earthquake with a low probability of occurrence is not economical and may still be unreliable due to the uncertainty surrounding seismic loading estimation. As a consequence, seismic design started to account for inelastic response while still conducting an elastic analysis using lower design force values. In recent years, significant advancements in earthquake engineering have resulted from a better knowledge of the dynamic behavior and seismic performance of buildings. The performance-based design method, in example, allows for the selection of a specific performance goal based on a variety of factors, including the owner's needs, the structure's functional usefulness, seismic risk, and possible economic losses, as a result, it's critical to assess these structures and enhance the seismic resistance of systems that have been identified as vulnerable.

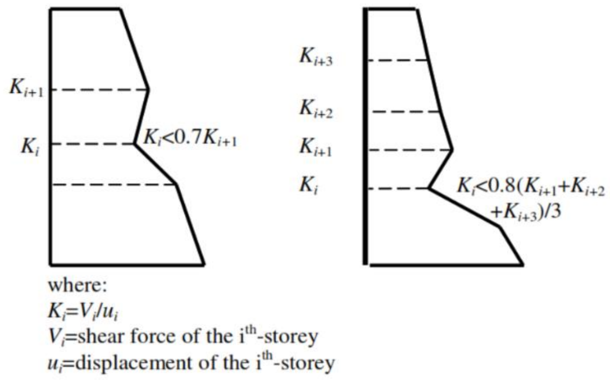


Figure 1: Lateral stiffness irregularity as defined by (ECP-201, 2012)

The stiffness, strength, ductility, and energy-dissipation properties of structural components, beside with other things, influence the behavior of RC structures. The loading redistribution capacity, which may fail if some of the members approach failure and the remaining ones cannot tolerate substantial deformations before failure, is in charge of the buildings' reaction. Some structural members' inadequate strength capability may be explained by the fact that they have been exposed to seismic loading demands that are considerably greater than those anticipated during their design process.

At the bottom level of a structure, there is a very common structural imperfection, this is due to these large spans are often required by architects in order to provide sufficient area for retail shops, garages, or just to avoid obstructing the aesthetic perspective, as a result, transfer-storey may be required. Under seismic activity, this kind of irregularity often causes the weaker floors to deform, causing the soft-storey mechanism. The failure of soft-stories was seen in several cases, whereas the remaining ones remained undamaged (or just had minor damage). In this study, member-level criteria, as suggested by (FEMA-356, 2000), was used to predict the afore-mentioned local failures and finally, compared to the global-level criteria, as has been adapted by past studies (Bai et al., 2017; Macrae et al., 2008) to provide the critical criteria and limits that should be studied for these types of buildings.

2. Soft Storey Vulnerability

If a storey's rigidity (usually ground floor) is considerably lower than the higher floors, a significant portion of lateral displacement concentrates on this first storey. This phenomenon maybe caused by variables, including floor's geometry, increased height and elements' dimensions. Although most seismic codesinclude measures to avoid soft storey in buildings, none of them provide a technique for calculating storey stiffness, and even though there are a lot of provisions for calculating the floor's stiffness, most of them gives different results. Therefore, a stiffness-loss calculation method is employed here where the primary structure is not changed in this method and as a result all the effective factors affecting storey stiffness, such as supportcondition, beam and column rotation, are taken into account.

Hence, the adapted method for stiffness calculation in this study is like that suggested by (Chinese National Specification, 2002; Geng & Xu, 2002) that involves modeling the transfer structure and the storey above it individually (each floor in a separate model with fixed base restraints) and applying a unit load and then $K_{p/t}$ (the loss of lateral stiffness between the transfer storey, (podium) and the regular storey above it (tower)) is calculated as follows:

$$K_{p/t} = \frac{\Delta_1}{\Delta_2} \tag{1}$$

Where Δ_1 and Δ_2 are the lateral drift of the transfer storey and the regular storey, respectively.

While a soft storey (irregularity in lateral stiffness) is defined by the National Specification and most of the building codes (including (ECP-201, 2012)) as a storey with lateral stiffness that is less than 70% of the storey above or less than 80% of the average stiffness of the three stories above (see Figure 1).

3. Non-linear procedures adapted in this study

Not only is the complex design of RC structures with vertical irregularities a problem, but sophisticated analytical methods are also required for evaluating these structures.

Non-linear seismic analysis technique is utilized in this article to get the most accurate assessments and findings, as explained below:

The adaptive pushover technique is a unique procedure, as the lateral load distribution is not maintained constant in this pushover technique but is constantly changed based on the modal shapes and participation factors obtained from the current step's eigenvalue analysis. Higher mode effects, as well as the stiffness state and period elongation of the structure at each step, are accounted for in this manner. The displacement-based version of the technique, in particular, addresses the inherent limitations of fixed-pattern displacement pushover by updating the lateral displacement patterns according to the system's continuously changing modal characteristics, resulting in better response estimates for irregular structures (which is the current study's point of interest). The analysis was carried out using the SeismoSruct software (Seismosoft, 2020), which is capable of simulating large deformations due to stiffness deterioration and material non-linearities. In SeismoStruct (Seismosoft, 2020), the so-called fiber approach is used to represent cross-section behavior, in which each fiber is associated with a uniaxial stress-strain relationship; the sectional stress-strain state of beam-column elements is then obtained by integrating the nonlinear uniaxial stress-strain responses of the individual fibers (typically 150 in this study), in which the section undergoes pushing towards non-linear stage by modeling it with a forcedbased distributed inelasticity formulation with the inelasticity concentrated inside a set length of the element, as suggested by (Scott & Fenves, 2006) and as seen in Figure 2.

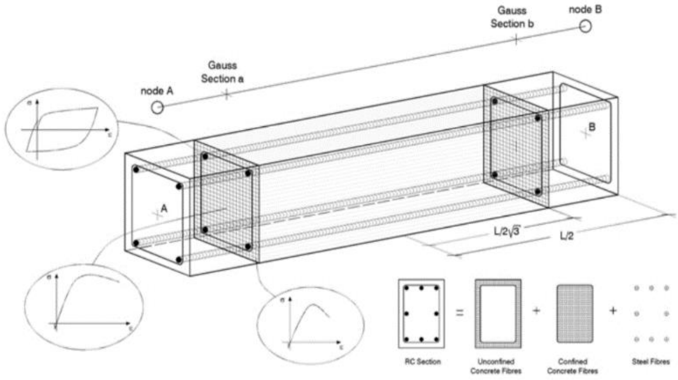


Figure 2: Decomposition of rectangular RC section (Elnashai A et al., 2003) and as adapted by SeismoStruct (Seismosoft, 2020)

4. EVALUATION CRITERIA AND ADAPTED ASSUMPTIONS

Seismic assessments were carried out utilizing the (FEMA-356, 2000) performance criteria based on the analytical findings. (FEMA-356, 2000) recommends two seismic assessment approaches: global and member-level, with three performance categories (immediate occupancy, life safety, and collapse prevention) as illustrated in Table 1.

Table 1 Damage Control and Building Performance Levels (FEMA-356, 2000)

	Target Building Performance Levels			
	Collapse Prevention Level (5-E)	**Life Safety Level (3-C)**	**Immediate Occupancy Level (1-B)**	**Operational Level (1-A)**
Overall Damage	Severe	Moderate	Light	Very Light
General	Little residual stiffness and strength, but load-bearing columns and walls function. Large permanent drifts. Some exits blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse.	Some residual strength and stiffness left in all stories. Gravity-load-bearing elements function. No out-of-plane failure of walls or tipping of parapets. Some permanent drift. Damage to partitions. Building may be beyond economical repair.	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. Elevators can be restarted. Fire protection operable.	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. All systems important to normal operation are functional.
Nonstructural components	Extensive damage.	Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged.	Equipment and contents are generally secure, but may not operate due to mechanical failure or lack of utilities.	Negligible damage occurs. Power and other utilities are available, possibly from standby sources.
Comparison with performance intended for buildings designed under the *NEHRP Provisions*, for the Design Earthquake	Significantly more damage and greater risk.	Somewhat more damage and slightly higher risk.	Less damage and lower risk.	Much less damage and lower risk.

To get more broad information on structural behavior and seismic performance, a member-level assessment of (FEMA-356, 2000) was conducted, utilizing plastic rotation limits, by pushing the structure till the initiation of the first mechanism at the transfer columns or transfer beams adapting the ‘’Strong-Transfer Weak-Tower’’ concept (as will be discussed later at this study) using the precise non-linear static method (Displacement-based Adaptive Pushover method (DAP)). The seismic response of the case study building was judged to see whether it was acceptable at various levels of performance. Top bounds of global maximum Inter-storey Drift Ratio (IDR_{max}) used to define the IO and LS performance levels have been set at 1% and 2%, respectively, for extra conservatism in the global failure criterion, the IDR for the CP level has been established at 3% (less than the 4% required by (FEMA-356, 2000)), as verified by other past studies (Broderick & Elnashai, 1995; Kappos, 1997). A summary of the chosen global and local damage criteria is presented below at Table 2.

Table 2: Adopted (chosen) global and local damage criteria ((FEMA-356, 2000)

Adopted Global-level Criteria (as per (FEMA-356, 2000))			Adopted Member-level Criteria (as per (FEMA-356, 2000))			
IO Performance Level	LS Performance Level	CP Performance Level		IO Performance Level	LS Performance Level	CP Performance Level
IDR_{max} (%)	IDR_{max} (%)	IDR_{max} (%)		Plastic rotation angle (radians)	Plastic rotation angle (radians)	Plastic rotation angle (radians)
1.00	2.00	3.00[a]	Columns	0.003	0.007	0.010
			Beams	0.005	0.005	0.015

[a] This is a more conservative upper bound (compared to the 4% suggested by (FEMA-356, 2000)) based on past findings as stated above.

5. Description of Prototype Buildings

5.1 General Description and Geometrical Configuration

The case study structure is built as a ten, fifteen, and twenty-storey with a transfer structure that has variable height and a variable stiffness. Fifteen prototype buildings, representative of the range of mid to high-rise buildings stock in Egypt, are selected to study the behavior of RC MRFs structures with transfer stories. Moment-resisting frames (MRFs) were chosen as the structural system because it reflects the type of concrete construction commonly used in Egypt and because its design is generally more controlled by drift limitations than shear wall systems or combined systems, and drift ratio is the response of interest in the proposed method, as discussed earlier.

The average floor height is 3m (for the buildings with 4.5m and 6m first floor-height, the average typical floor height is 2.9m and 2.8m respectively, to achieve the same total building height for a fair comparison), whereas the ground transfer floor (as common in contemporary Egyptian usage due to the need of commercial areas at ground floor where columns interfere the aesthetic frontages) is varied between 3, 4.5, and 6 meters of clear height. Spans and columns layout are assumed to preserve generality in the adapted buildings.

Notation, adapted in this study, is as follows: YYS-ZH-Kp/t-III. Where YY is the number of stories (e.g., 15S for the building with 15 stories), and Z for the height ratio between transfer storey and first storey of the first floor (e.g., 1.5H for the building with first story height equals to 4.5 m, as typical storey height, adapted in this study, is 3.0 m). And III is either max. or min. reflecting two categories for both the 1.5H and 2H cases ($K_{p/t\text{-}min}$ and $K_{p/t\text{-}max}$ for the cases with different ranges of lateral stiffness loss as will be discussed latter in this study). The prototype buildings' configurations and notations are summarized in Table 3, and their elevations are shown in Figure 4.

5.2 Design Details and Assumptions

According to the Egyptian Code of Practice (ECP-201, 2012; ECP-203, 2017) which are fundamentally in line with the regulations of Eurocode 8 (CEN, 2004), a typical modern seismic code applicable to many countries with different seismicity, soil conditions, and construction practice, the buildings are designed and detailed to resist a combination of gravity and seismic loads. For gravity load design, dead loads comprise the structure's own weight, a typical floor cover of 2.0kN/m2, and an intensity of 1.5kN/m3 for partition (wall) loads, includingplastering and assuming normal wall thickness of 250 mm. Additionally, a live load of 3.0kN/m2 is considered. On the other hand, for seismic design reasons, a total seismic mass is included, which includes self-weight and floor cover plus 50% of the living load. Limited ductility frames are selected based on the norm of reinforcement details in Egypt and many other countries with comparable low-to-moderate seismicity, and therefore a FRF with a value of 5 is utilized in the design. Materials with 30 N/mm2 and 360 N/mm2 are assumed for the 28-days compressive RC cube strength and the steel reinforcement yield strength, respectively.

6. STIFFNESS CATEGORIZATION

Due to the vertical irregularity in the form of transfer structure that results in a significant strength loss at the transfer storey with respect to the contiguous floors, which represents the most threat for these types of vertically irregular structures as the sudden change in the building's lateral stiffness at its level becomes vulnerable to the development of a soft-storey mechanism. Hence, the amount of stiffness loss must be quantitively measured as stated by Equation (1) to give a certain $K_{p/t}$ value for the occurrence or the avoidance of the soft-storey mechanism.

After numerous investigations, in this study, of these types of vertically irregular structure, two definitions of soft-storey mechanism are presented, as follows:

1- The formation of any mechanism at the transfer storey prior to the exceedance of global-level criteria for a given performance level (initiation of chord rotation (θ_p) member-level criteria prior to the exceedance of the (IDR_{max}) global-level criteria for IO, LS, and CP performance levels). This is also compliant with what Professors R. Park and T. Paulay developed (Park et al., 1975), which is a capacity design concept in which the optimum locations of plastic hinges are selected. According to capacity design philosophy, selecting an appropriate plastic mechanism is the first step in effectively constructing a ductile earthquake-resistant structure. Figure 3 depicts mechanism for a transfer-storey structure based on the strong-transfer and weak-upper structure theories. The potential plastic hinges of the transfer-storey shape shown may be formed at the ends of frame beams (D), the ends of upper coupling beams (F), and the lowest of higher shear partitions (G), providing ductility to the entire structure while other structural elements remain elastic at some point during seismic excitation. Consequently, monitoring member-level criteria for key components in capacity design, as ground shear walls (A), lower supporting columns (B), conventional transfer girders (H), and cantilever ones (I) (Yang Kun., 2005; Zheng Yi., 2003), is carried out in accordance with (FEMA-356, 2000).

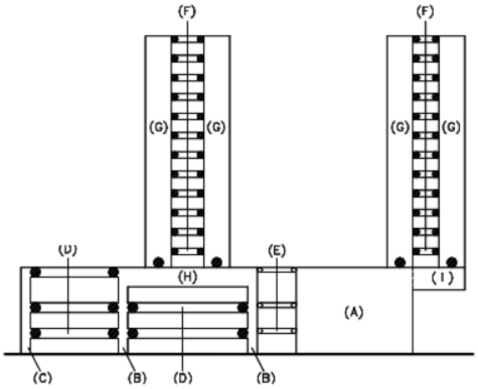


Figure 3: Plastic Mechanism Based on Strong Transfer and Weak Upper Structure Theory (Yang Kun., 2005; Zheng Yi., 2003)

2- The building's collapse mechanism occurs at the transfer storey where the IDR concentrates (a significant decrease of the IDR profile, along the height of the building, from the transfer storey to the storey above it). In other words, the dissimilarity of the IDR profile, along the building's height, compared to its regular counterpart (at which the IDR profile is smoothly increased from transfer storey to the storey above resulting in the favorable cantilever global deformation shape).

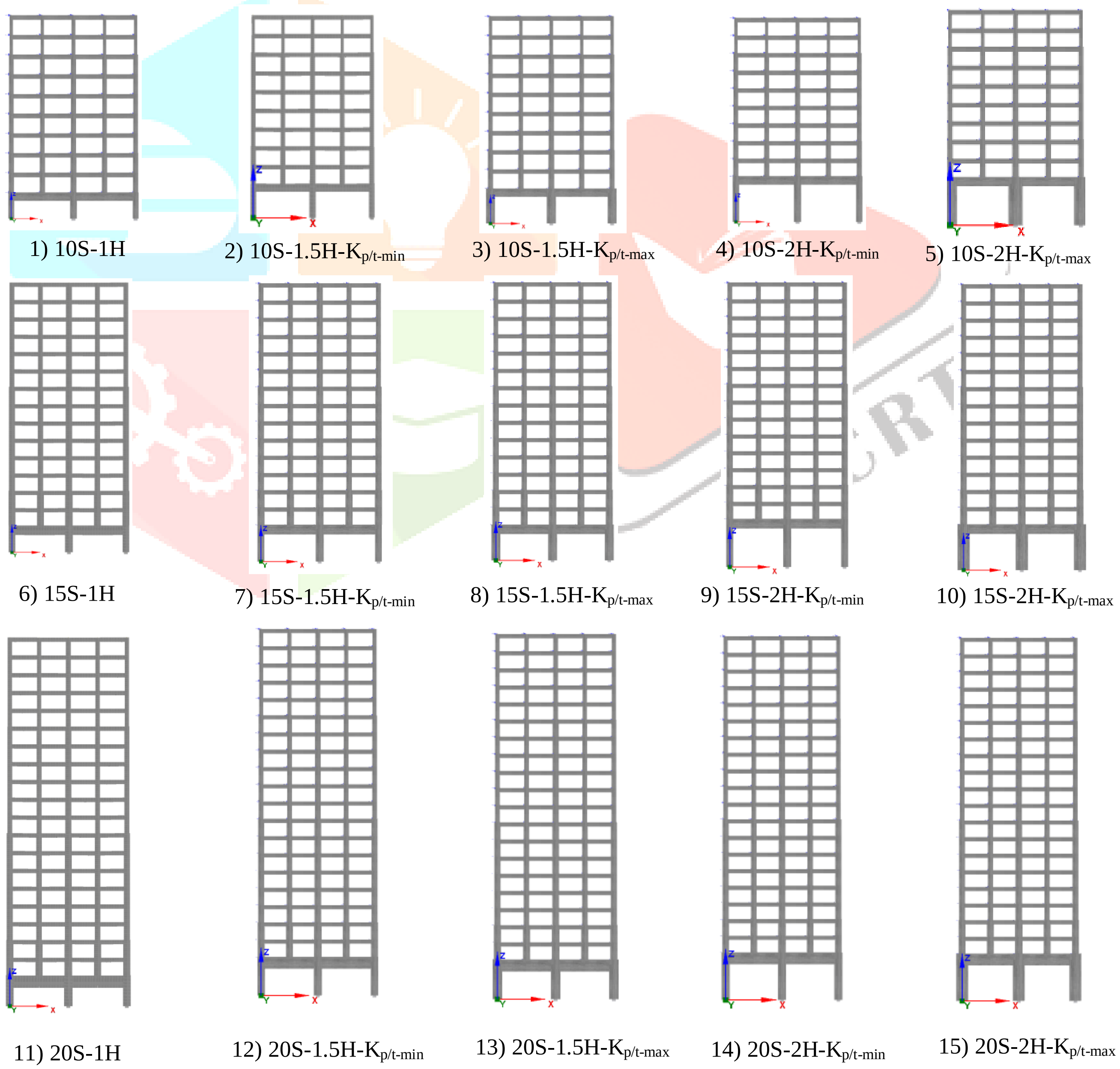


Figure 4: Front elevation of the fifteen case study buildings

Table 3: Sizes and reinforcement of structural members of case study prototype

Building type[a]	Outer columns		Inner columns		Beams		
	Story #	Size (mm)/RFT (%)	Story #	Size (mm)/RFT (%)	Story #	Size (mm)	RFT
10S-1H	(Transfer)	900/1.45	(Transfer)	1000/1.57	(Transfer)	900x1300	18Φ32
	2-3	800/1.53	2-3	900/1.45	2-3	500×700	6Φ20
	4-7	700/1.23	4-7	800/1.2	4-7	300X700	4Φ20
	8-10	500/1.37	8-10	600/1.75	8-10	300X700	4Φ20
10S-1.5H-$K_{p/t-max}$	(Transfer)	1350/1.49	(Transfer)	1350/1.52	(Transfer)	900x1300	18Φ32
	2-3	800/1.53	2-3	900/1.45	2-3	500×700	6Φ20
	4-7	700/1.23	4-7	800/1.2	4-7	300X700	4Φ20
	8-10	500/1.37	8-10	600/1.75	8-10	300X700	4Φ20
10S-2H-$K_{p/t-min}$	(Transfer)	1000/1.53	(Transfer)	1100/1.49	(Transfer)	900x1300	18Φ32
	2-3	800/1.53	2-3	900/1.45	2-3	500×700	6Φ20
	4-7	700/1.23	4-7	800/1.2	4-7	300X700	4Φ20
	8-10	500/1.37	8-10	600/1.75	8-10	300X700	4Φ20
10S-2H-$K_{p/t-max}$	(Transfer)	1850/1.61	(Transfer)	1850/1.61	(Transfer)	900x1300	18Φ32
	2-3	800/1.53	2-3	900/1.45	2-3	500×700	6Φ20
	4-7	700/1.23	4-7	800/1.2	4-7	300X700	4Φ20
	8-10	500/1.37	8-10	600/1.75	8-10	300X700	4Φ20
15S-1H	(Transfer)	1100/1.62	(Transfer)	1300/1.1.76	(Transfer)	1000/1600	20Φ32
	2-3	1000/1.53	2-3	1150/1.57	2-3	500/700	6Φ20
	4-9	900/1.45	4-9	900/1.45	4-9	300X700	4Φ20
	10-15	800/1.38	10-15	800/1.38	10-15	300X700	4Φ20
15S-1.5H-$K_{p/t-max}$	(Transfer)	1350/1.49	(Transfer)	1350/1.49	(Transfer)	1000/1600	20Φ32
	2-3	1000/1.53	2-3	1150/1.57	2-3	500/700	6Φ20
	4-9	900/1.45	4-9	900/1.45	4-9	300X700	4Φ20
	10-15	800/1.38	10-15	800/1.38	10-15	300X700	4Φ20
15S-2H-$K_{p/t-min}$	(Transfer)	1150/1.34	(Transfer)	1300/1.39	(Transfer)	1000/1600	20Φ32
	2-3	1000/1.53	2-3	1150/1.57	2-3	500/700	6Φ20
	4-9	900/1.45	4-9	900/1.45	4-9	300X700	4Φ20
	10-15	800/1.38	10-15	800/1.38	10-15	300X700	4Φ20
15S-2H-$K_{p/t-max}$	(Transfer)	1900/1.56	(Transfer)	1900/1.56	(Transfer)	1000/1600	20Φ32
	2-3	1000/1.53	2-3	1150/1.57	2-3	500/700	6Φ20
	4-9	900/1.45	4-9	900/1.45	4-9	300X700	4Φ20
	10-15	800/1.38	10-15	800/1.38	10-15	300X700	4Φ20
20S-1H	(Transfer)	1250/1.90	(Transfer)	1350/1.63	(Transfer)	1000/2000	24Φ32
	2-3	1150/1.41	2-3	1250/1.44	2-3	500/700	6Φ20
	4-9	900/1.61	4-9	1150/1.44	4-9	300X700	5Φ20
	10-15	800/1.53	10-15	1000/1.18	10-15	300X700	4Φ20
	16-20	700/1.26	16-20	800/1.23	16-20	300x700	4Φ20
20S-1.5H-$K_{p/t-max}$	(Transfer)	1400/1.61	(Transfer)	1400/1.61	(Transfer)	1000/2000	24Φ32
	2-3	1150/1.41	2-3	1250/1.44	2-3	500/700	6Φ20
	4-9	900/1.61	4-9	1150/1.44	4-9	300X700	5Φ20
	10-15	800/1.53	10-15	1000/1.18	10-15	300X700	4Φ20
	16-20	700/1.26	16-20	800/1.23	16-20	300x700	4Φ20
20S-2H-$K_{p/t-min}$	(Transfer)	1350/1.61	(Transfer)	1350/1.61	(Transfer)	1000/2000	24Φ32
20S-2H-$K_{p/t-min}$	2-3	1150/1.41	2-3	1250/1.44	2-3	500/700	6Φ20
	4-9	900/1.61	4-9	1150/1.44	4-9	300X700	5Φ20
	10-15	800/1.53	10-15	1000/1.18	10-15	300X700	4Φ20
	16-20	700/1.26	16-20	800/1.23	16-20	300x700	4Φ20
20S-2H-$K_{p/t-max}$	(Transfer)	2000/1.47	(Transfer)	2000/1.47	(Transfer)	1000/2000	24Φ32
	2-3	1150/1.41	2-3	1250/1.44	2-3	500/700	6Φ20
	4-9	900/1.61	4-9	1150/1.44	4-9	300X700	5Φ20
	10-15	800/1.53	10-15	1000/1.18	10-15	300X700	4Φ20
	16-20	700/1.26	16-20	800/1.23	16-20	300x700	4Φ20

[a] The 1.5H-$K_{p/t-min}$ buildings are not included in the table, as their dimensions are a replica of their 1H counterparts.

7. Study Procedure

The procedure to study of the behavior of these irregular buildings is as follows:

a- For every chosen number of stories (adapted here, in this study: 10, 15 and 20) it was firstly assumed that the transfer storey has a clear height equal to that of the typical storey (H=3m), and the building was designed according to the (ECP-203, 2017) and in conjunction with (ECP-201, 2012) by applying the minimal possible safe sections (in order to be as conservative as possible when being generalized for the future use). For this type of buildings (1H (as notated in this study)) the structure's behavior guaranteed a good similarity to that of a regular counterpart, therefore there is no need to study different values of $K_{p/t}$ in this category.

b- For every chosen number of stories (adapted here, in this study: 10, 15 and 20) it was then assumed that the transfer storey has a clear height equal to 1.5 and 2 times that of the typical storey (clear height equals 4.5 and 6 m, respectively) and the building was designed according to the (ECP-203, 2017) and in conjunction with (ECP-201, 2012) by applying the minimal possible safe sections (in order to be as conservative as possible when being generalized for the future use) and by applying Displacement-based Adaptive Pushover method (DAP) it was observed that, even being designed by the Egyptian code's response spectrum and under design load combinations, these types of buildings experience a distinct loss in the capacity curve and concentration in the IDR at the first floor, revealing the initiation of mechanisms at the transfer storey. Therefore, the need arises to study another version, which the designer may prefer, of this type. This version is the stiffer one (by applying increase in transfer structure columns' dimensions), in which several $K_{p/t}$ values were tried and studied till the soft-storey mechanism, defined above with two conditions, is diminished. Finally, this boundary value is obtained for each type of structure studied after several iterations. Therefore, two categories were studied, one with $K_{p/t}$ less than 0.6, 0.65, and 0.7 for the 20S, 15S, and 10S buildings, respectively, notated as $K_{p/t\text{-}min}$ and the other with $K_{p/t}$ values bigger than the afore-mentioned values and notated as $K_{p/t\text{-}max}$.

8. Results and Discussion

At the occurrence of each damage limitation value, all IDR related to the occurrence of member-level criteria are monitored. Figures from 5 to 9 present the IDR_{max} along the structure's height, with each prototype building's graph displayed individually for clarity. For the adapted prototype buildings and as the height increases, flexural-type behavior (like a cantilever's deformation) can be seen near the lower stories due to significant axial deformation of the columns carrying the entire building, then the lateral deformation changes back to overall shear-type behavior at higher floor levels, when the axial load levels decrease. These findings are common in well-designed low-to-medium-rise moment frame structures. Because of the greater mass vibrating in these modes, the contribution of higher modes of vibration is especially noticeable in the displacement forms of taller structures, as also shown by the following graph:

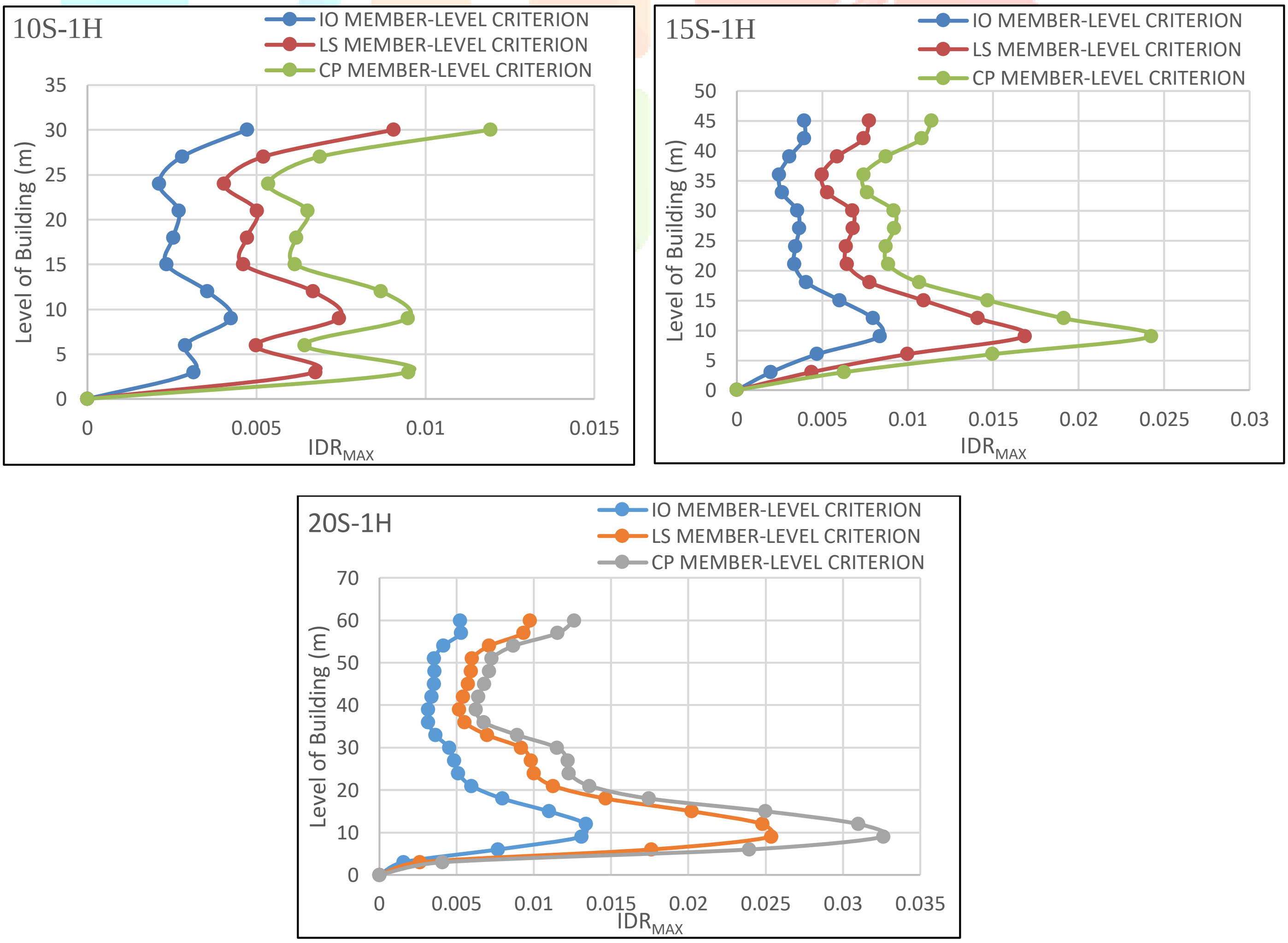


Figure 5: IDR_{max} along building's height for the 1H case study buildings

For the 1H buildings, it is found that 15S and 20S buildings are nearly similar, in behavior, to their regular counterparts. Although, as the building's height increases the member-level criteria become less critical, the reason for the difference in $K_{p/t}$ values between the three buildings' heights is that shorter buildings are stiffer than taller ones; thus, taller buildings can sustain global damage more easily than their shorter counterparts, allowing for the exceedance of global-level criteria prior to the member-level ones. As shown above, the IDR_{max} corresponding to CP member level criteria are 1.3, 2.4, and 3.3% for the 10S, 15S, and 20S, respectively.

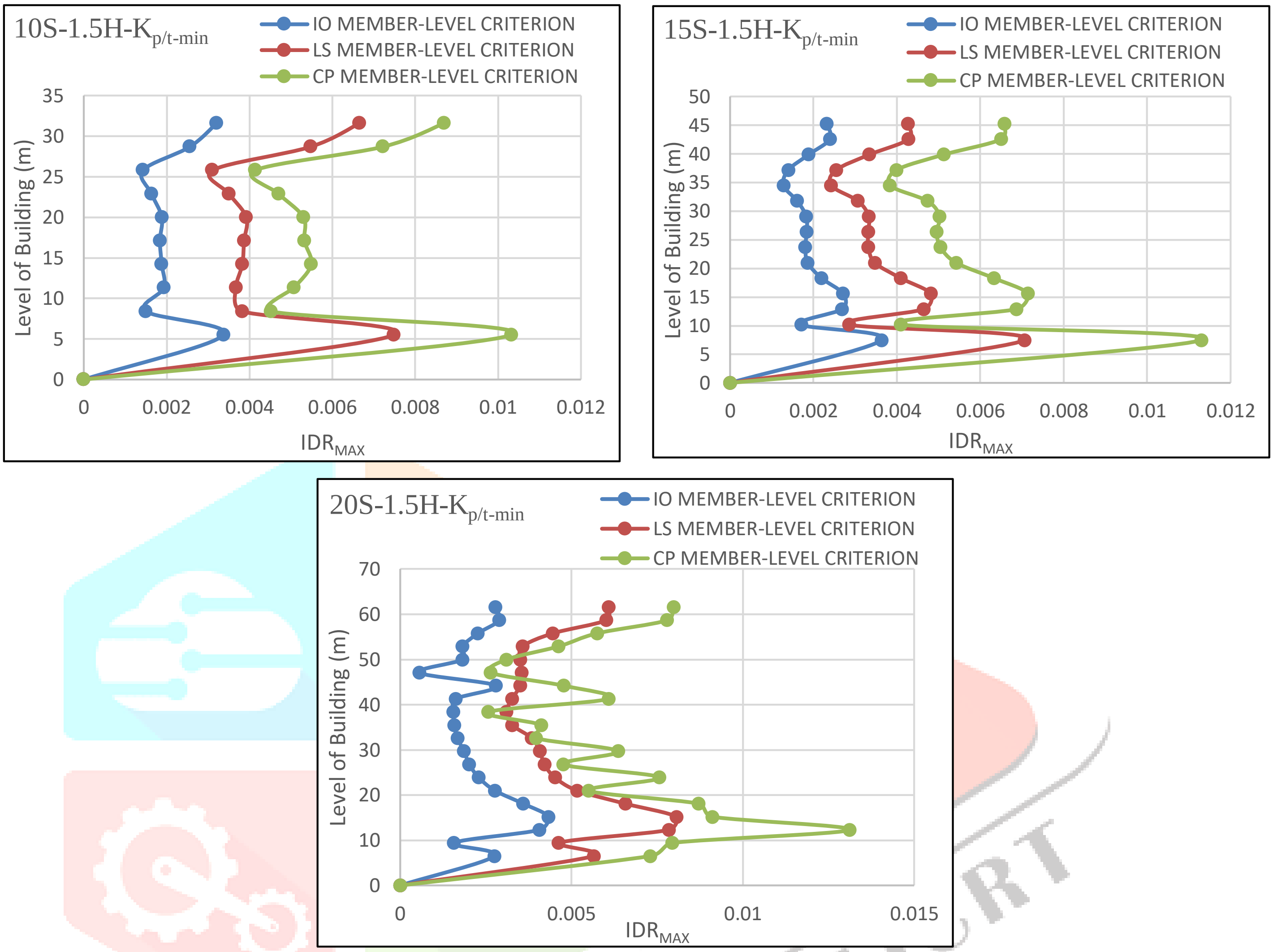
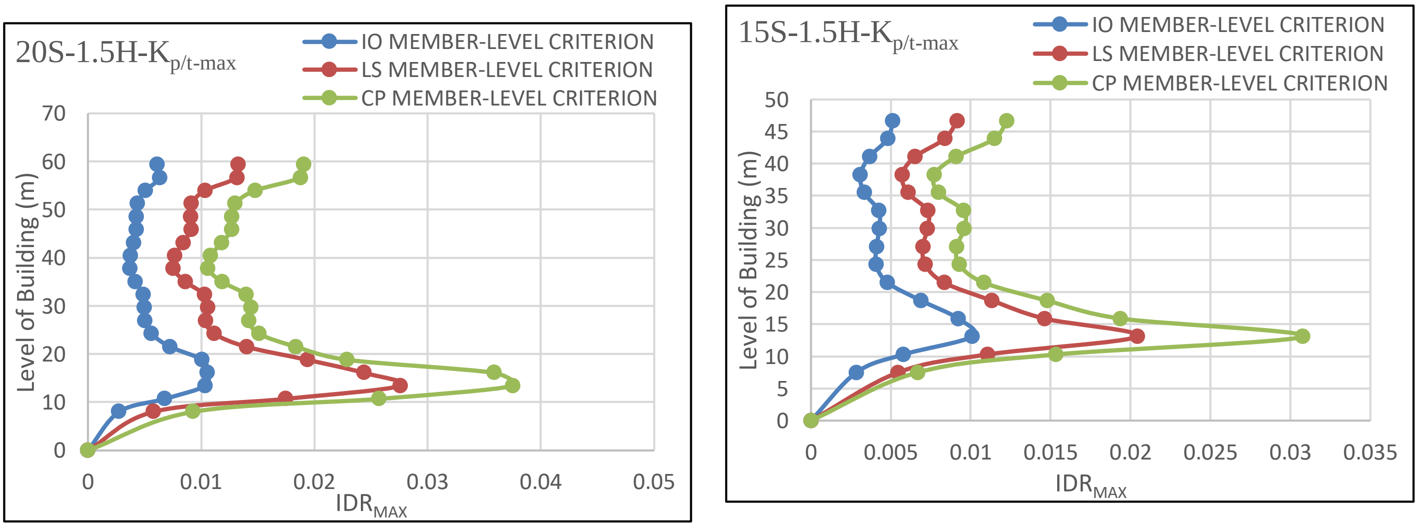


Figure 6: IDR_{max} along building's height for the 1.5H-$K_{p/t\text{-}min}$ case study buildings

For the 1.5H-$K_{p/t\text{-}min}$ buildings, the buildings experience an abrupt increase in the IDR at the transfer storey (as seen from the difference between the IDR at the transfer storey and the storey above it), however the IDR_{max} is still not occurring at the transfer storey. It can also be observed that the storey just above the transfer one is experiencing a rapidly increase IDR between the three performance levels, this is due to that even though the building is designed in accordance with (ECP-201, 2012) provisions and strength, the big IDR at the transfer storey affects the monolithically joined columns of this floor (planted columns on transfer beams) causing an abrupt strength loss for the storey just above the transfer floor.



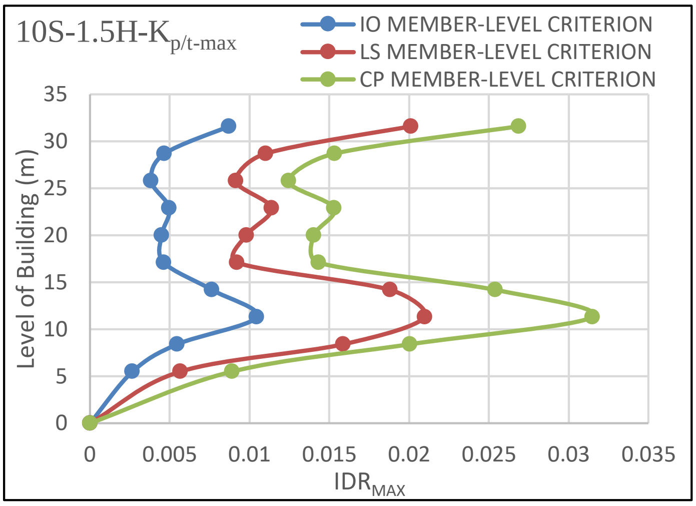


Figure 7: IDR_{max} along building's height for the 1.5H-$K_{p/t-max}$ case study buildings

For the 1.5H-$K_{p/t-max}$ buildings, after numerous iterations, as mentioned before, it was found that in order to achieve a stiff structure without the threat of a transfer storey (the IDR_{max} occurring at the initiation of plastic rotation limits, as suggested by (FEMA-356, 2000), is equal to that occurring at the global-level criteria) the $K_{p/t}$ values are 0.6, 0.65, and 0.7 for the 20S, 15S, and 10S buildings, respectively. This results in overcoming the soft-storey mechanism and a uniform IDR (nearly compatible with the favorable cantilever's deformation of regular counterpart) is guaranteed. The $K_{p/t}$ values show high compatibility with that suggested by international codes (including (ECP-201, 2012) and as seen in Figure 1), although the stiffness loss calculation method is advised to be calculated as the proposed equation (Equation 1). The reason of the variation in the value of $K_{p/t}$ between the three building's height is that shorter buildings are stiffer than taller ones, consequently, taller buildings achieve global damage easier than the shorter counterparts allowing for a more stiffness loss between the first and transfer floors ($K_{p/t)}$ while achieving the same behavior compared to the more restricted $K_{p/t}$ values for the shorter counterparts.

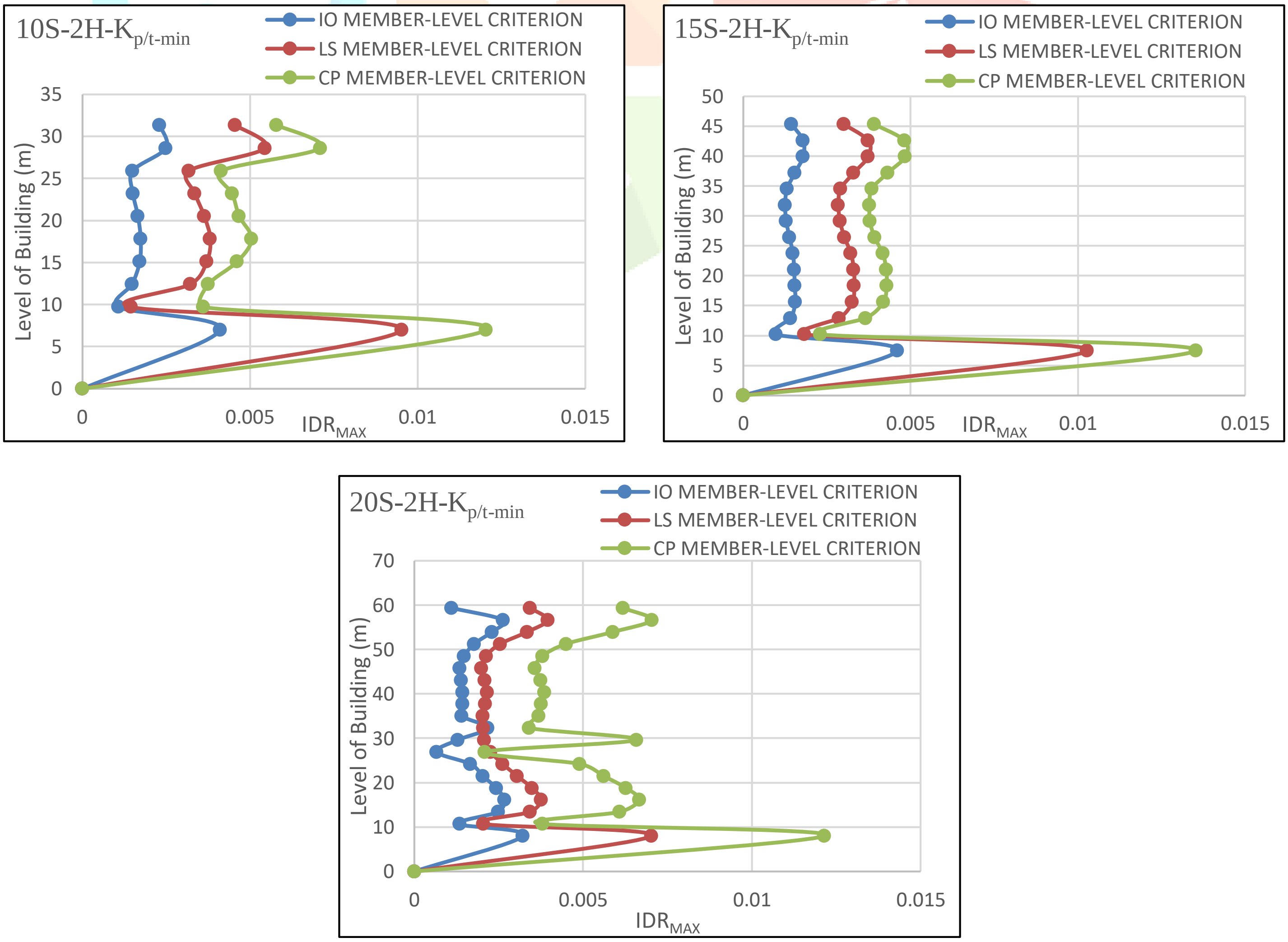


Figure 8: IDR_{max} along building's height for the 2H-$K_{p/t-min}$ case study buildings

For the 2H-$K_{p/t-min}$ buildings, although being designed in conjunction with (ECP-203, 2017) and satisfying code provisions, it experiences a threatening clear soft-storey mechanism failure behavior. It may be not that disastrous when studied at the first performance level (IO) as the IDR at the transfer storey is of nearly similar values to other stories at the upper part of the building, but as the drift increases, the P-Delta effect at this week transfer storey causes the abrupt increase in the IDR that leads to the soft-storey failure mechanism of these types of buildings, this effect increases as the building's height increases and this can be observed clearly from the graphs.

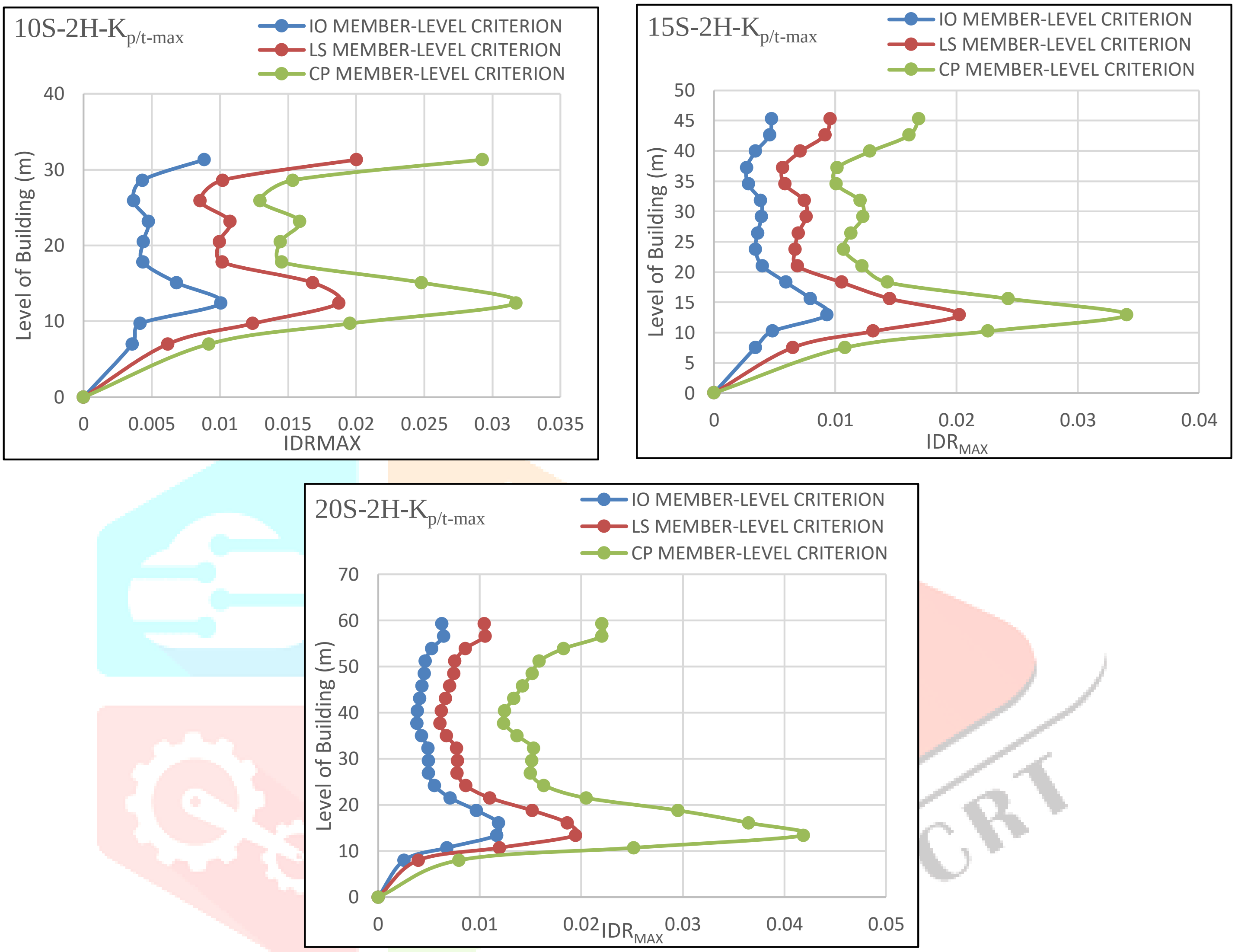


Figure 9: IDR_{max} along building's height for the 2H-$K_{p/t-max}$ case study buildings

For the 2H-$K_{p/t-max}$ buildings, with a stiff transfer storey having $K_{p/t}$ values more than 0.6, 0.65, and 0.7 for the 20S, 15S, and 10S buildings, respectively (as stated above), and successfully overcoming the soft-storey mechanism even though it has a relatively big height compared to the typical storey. A uniform IDR (nearly compatible with the favorable cantilever's deformation of regular counterpart) seems to be successfully attained.

After the non-linear analysis done and based on the graphs shown above and conclusions, and after providing a recommended values of acceptable stiffness loss limits between the first (transfer) and second floors ($K_{p/t}$), a set of recommended values of critical IDR_{max} limits are provided for the adapted case study buildings and their counterparts.

The only two categories that are not governing, when compared to the global limits (presented by the black dashed line), are the stiff version of the 1.5H and the 2H buildings of all heights, in addition to the twenty-storey building with the transfer storey height equal to that of the typical one (20S-1H) which shows critical global IDR limits when compared to the local ones, this is due that shorter buildings are stiffer than taller ones, consequently, taller buildings achieve global damage easier than the shorter counterparts allowing for a more stiffness loss between the first and transfer floors ($K_{p/t}$) while achieving the same behavior compared to the more restricted $K_{p/t}$ values for the shorter counterparts as mentioned before. On the same line, the IDR limits based on member-level criteria is much higher, although still lower than that based on global criteria, at the fifteen-storey buildings compared to the ten-storey buildings. For the IO performance level, usually associated with the Frequently Occurring Earthquake (FOE), all the case studies with $K_{p/t-min}$ seems to have nearly the same values, this is due to that the plastic rotation limit, recommended by (FEMA-356, 2000), associated with this performance level is restrictively low, not allowing for the P-Delta effect to take place, hence the three building's heights nearly attain the same results for this performance level. While for the LS and CP performance levels, where mechanisms at other stories already happened and P-Delta effect has considerable effect, the $K_{p/t-min}$ buildings are found to have a threateningly lower IDR_{max} values based on member-level criteria than that based on the global-level, also as the building height increase these values decrease becoming more critical. Although, they are still fairly similar to each other's.

These values are provided at the three following graphs, as follows:

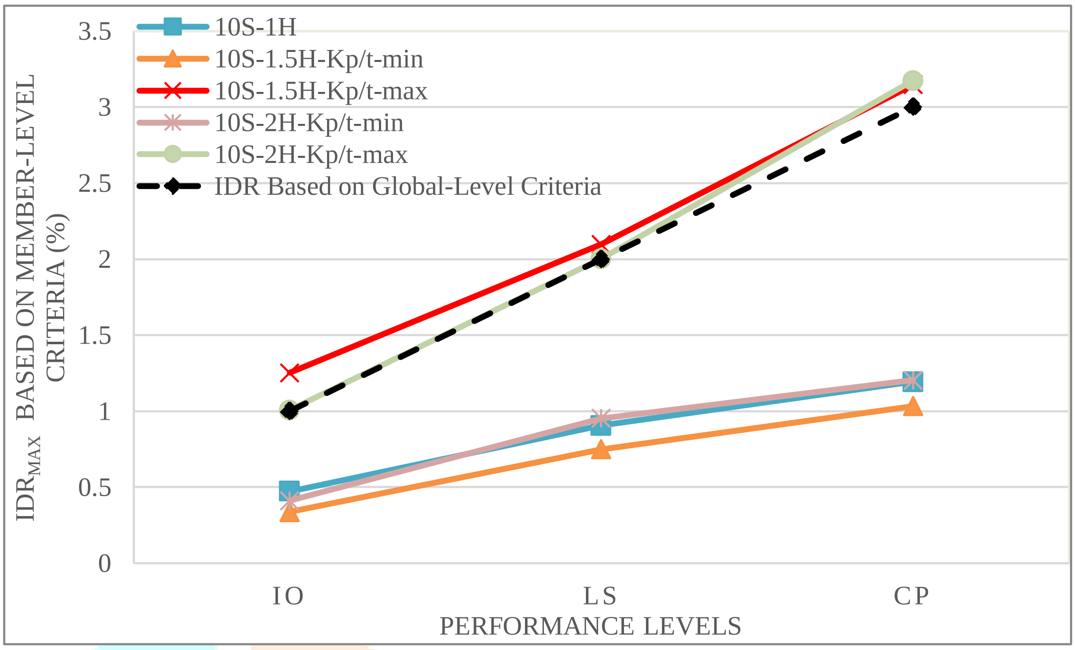


Figure 10: IDR_{max} based on member-level criteria for the 10S case study buildings

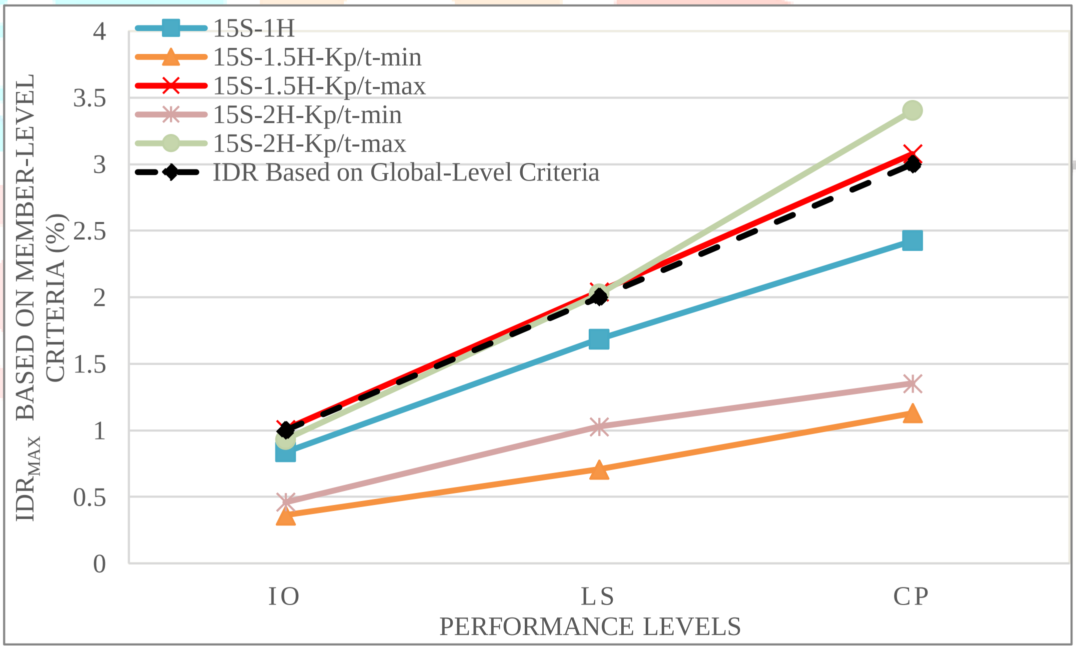


Figure 12: IDR_{max} based on member-level criteria for the 15S case study buildings

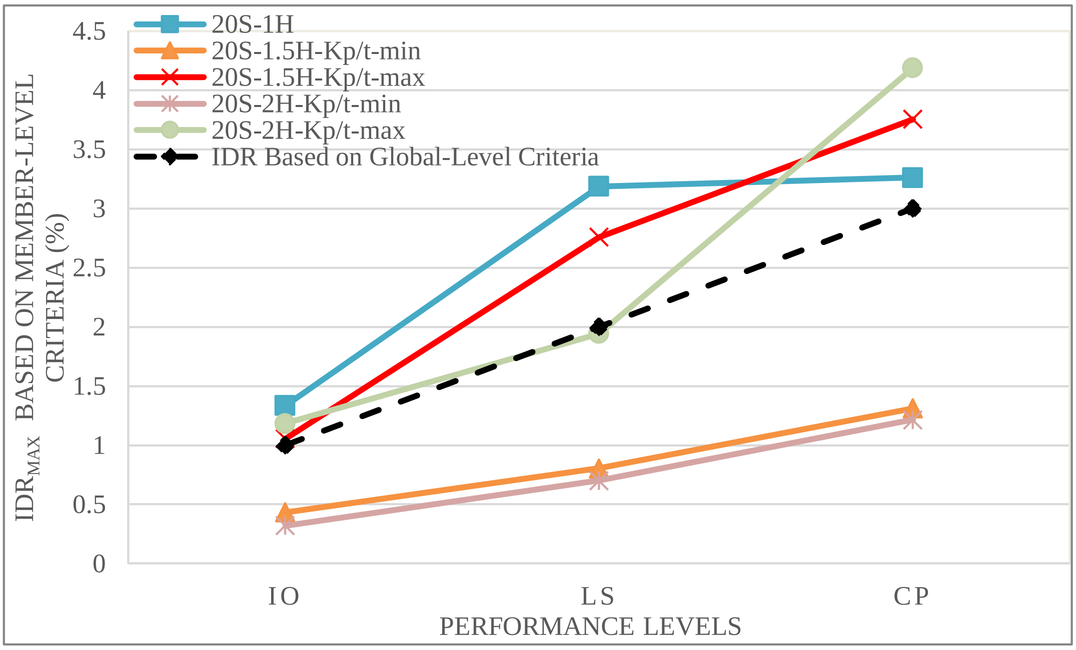


Figure 12**:** IDR_{max} based on member-level criteria for the 20S case study buildings

9. CONCLUSIONS

In this study, the vulnerability of unpredictable damage (unpredicted when investigated by linear and conventional methods) of vertically irregular structures in the form of buildings with transfer storey, having variable heights and stiffnesses, is investigated by applying the newly developed non-linear static analysis (Displacement-based Adaptive Pushover method), which is applicable for these types of vertically irregular RC structures as it accounts for the higher modes, material degradation, and stiffness deterioration effects. Fifteen prototype case studies, designed according to the Egyptian Code of Practice (ECP-203, 2017)and in conjunction with (ECP-201, 2012) (which are fundamentally in line with the regulations of Eurocode 8 (EN 1998-1, 2004)), are investigated considering the afore-mentioned variables. (FEMA-356, 2000) member-level criteria were used to investigate the formation of local mechanisms at the transfer storey and compared to the corresponding global damage to assess different types of failures including the unfavorable soft-storey mechanism.

As a consequence of the analysis, a set of findings has been reached, as indicated below:

a. The soft-storey mechanism is found to have a disastrous effect in lowering the structure's capacity to withstand seismic loads, prompting the development of global IDRs that are significantly lower than those suggested by (FEMA-356, 2000) global criteria, as has achieved in this study, and always, as a consequence, will increase the need for force-based design of these types of irregular structures with a lower value of force reduction factor (R) than that suggested by (ECP-201, 2012).

b. Using adaptive push-over analysis, the drift limits based on member-level criteria were established. As a result, member-level (plastic rotation) drift limits based on (FEMA-356, 2000) criteria did not match the global-based one. For most of the cases, (FEMA-356, 2000) global-level (drift) limitations tended to be lower as well. This is because the drift limits for member-level criteria are influenced by the stiffness degradation present at the transfer storey which is the main cause of soft-storey mechanism failures.

c. The global level drift limitations may offer a more universal benchmark for comparing the seismic fragility of the case study structure to other kinds of structures. However, the (FEMA-356, 2000) member-level or other quantitative limitations are suggested for a more detailed assessment. Because these drift limits were established utilizing a comprehensive structure-specific analysis, they better represent the case study structure's features and susceptibility to deterioration.

d. The (FEMA-356, 2000) global-level criteria show a good compliance with the regular building's deformation shape. In other words, for structures having IDR_{max} that corresponds to the initiation of member-level criteria equals to IDR_{max} limits suggested by (FEMA-356, 2000) global-level criteria, a smooth deformation shape, with no drift concentrations at any floor and thus no soft-storey mechanism risk, is guaranteed.

e. In buildings with soft stories, extra safety measures should be taken at the upper and lower ends of the ground storey columns, some of these measures include enlarging the cross section of the column at the lower and higher ends, as well as increasing stirrups spacing. Studies in this approach should be conducted to provide clarity.

f. Being designed in accordance with the ECP and applying minimum possible safe sections and despite of having different building's height, all the three building heights with a transfer storey height equal to 1.5 or 2 times that of the typical storey (1.5H and 2H) gives promising equal performance limits for the three performance levels, and hence the values shown in Figures 10, 11, and 12 can be widely used with similar-type buildings having different heights.

g. After numerous iterations, it was found that the $K_{p/t}$ values (the loss in stiffness between transfer storey and storey above) for the 20S, 15S, and 10S buildings, respectively, are 0.6, 0.65, and 0.7 in order to achieve a stiff structure without the threat of a transfer storey (the IDR_{max} occurring at the initiation of plastic rotation limits, as suggested by (FEMA-356, 2000), is equal to that occurring at the global-level criteria). As a consequence, the soft-storey mechanism is bypassed, and a uniform IDR (almost equivalent with the normal counterpart's desirable cantilever deformation) is ensured.

h. Shorter buildings require more strict limits for stiffness loss allowance between floors, this is because those shorter buildings are stiffer than taller ones, as a result, taller buildings suffer global damage more easily than their shorter counterparts, allowing for more stiffness loss between the first and transfer floors ($K_{p/t}$) while maintaining the same behavior as the more restricted $K_{p/t}$ values for the shorter counterparts. The difference in $K_{p/t}$ values between the three buildings' heights is a consequence of this.

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