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# Second-Order Behavior and Carrying Capacity of 3D Asymmetric Steel frames With Bracing Elements

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**Abstract**

Non-linear P-delta behavior of three-dimensional frames with plan and elevation asymmetries is studied, using a parametric variation of geometry in plan and a stiffness variation along the height. Some behavioral aspects of a calibration frame have been addressed to ascertain the importance of the nodal rigidity (modeled with laminar elements of the type shell with implicit formulation of thick plate or modeled with elastic stiff springs) in the modeling of the geometric non-linearity and stability of such calibration frame. Eurocode 3 criteria for second order analyses is briefly addressed in connection with the 2D frame classification with respect to sway behavior; however for 3D structures the calculated carrying capacity is independent of this classification. So a parametric study of the critical load factor of asymmetric three-dimensional frames, unbraced and braced, permits to characterize their carrying capacity with respect to overall structural stability.

**Key words**: Non-Linear Geometric Structural Analysis, Stability of Asymmetric 3D Frames, Bracing of Structures, Modeling of Connections.

## 1. Introduction

This study departs from previous works of the authors (Cesar and Barros [1][2]) that used a calibration frame for assessing the validity and accuracy of some available commercial software (namely ANSYS [3], LUSAS [4] and SAP 2000 [5]) as well as of the authors developed software INST3D (Barros and Cesar [6]) in determining the critical load factor of side-sway prevented and side-sway free frames; thereafter INST3D, ANSYS and SAP were used concurrently in characterizing the non-linear carrying capacity of 3D metallic frames (braced and unbraced) with plan asymmetries.

Thereafter, the main emphasis of this work is on parametric studies of the non-linear geometric behavior and carrying capacity of 3D asymmetric steel frames, with plan and elevation asymmetries.

## 2. Eurocode 3 criteria for 2nd order analyses

In this section a design code remark from Eurocode 3 - EC3 [7] [8] is made, to ensure that in this study is guaranteed the structure serviceability. In this design code a 2nd order analyses is not necessary when the structure is braced in such a way that the lateral displacement is reduced in 80% relatively to the unbraced configuration (Fig. 1) and also when the structural system can be classified as an un-sway frame, which is the same as insuring that $\alpha_{critical} \geq 10$ (Fig. 2).

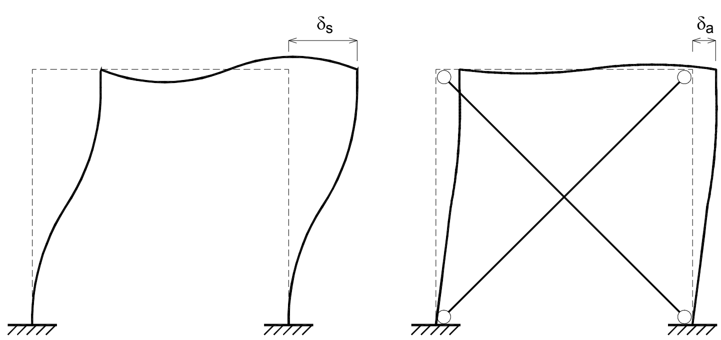
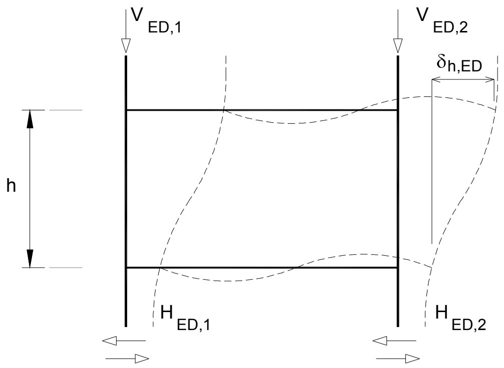



Fig. 1 – Eurocode 3 braced frame classification criteria




$$\alpha_{crit} = \left( \frac{h}{\delta_{H,Ed}} \right) \cdot \left( \frac{H_{Ed}}{V_{Ed}} \right) = \frac{V_{cr}}{V_{Sd}} \geq 10$$

Fig. 2 – Eurocode 3 un-sway classification criteria

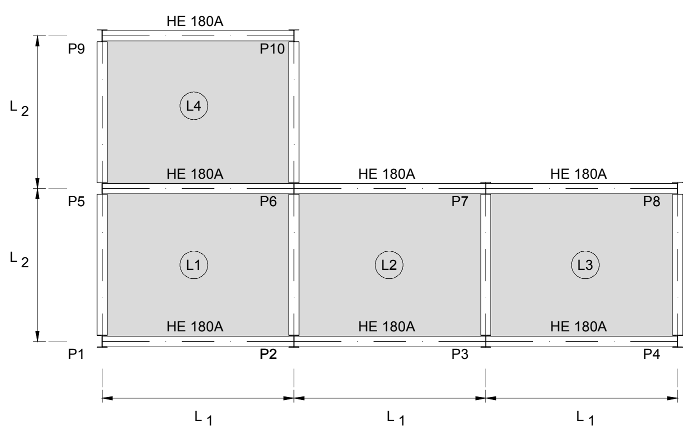
These criteria were used in this work to ensure the efficiency of the bracing system selected. When the structure is classified as a sway frame, EC3 allows performing a simplified 2nd order analysis like the moment magnification method (only for Vsd / Vcr $\leq$ 0.25).

According to the EC3, the structural serviceability can be verified limiting the inter-story drift by the allowed code drift (usually limited to H/300, in which H is the inter-story height).

## 3. Parametric Study on the Carrying Capacity of 3D Frames with Plan and Elevation Asymmetries

After software calibration some parametric studies have been elaborated on the carrying capacity of geometrically non-linear 3D steel frames. One of the analyzed structures is a 5-floor 3D building frame with plan asymmetry, braced and unbraced, whose initial results were previously presented by Barros and Cesar [2].

In Fig. 3 the plant view of the asymmetric building is shown with the indication of the numbering of the 2D slabs that compose the represented 3D structure. This figure also gives the column profiles of HE series, allocated to each floor of the modeled 2D frames.




| | 1st floor | 2nd floor | 3rd floor | 4th floor | 5th floor |
|---|---|---|---|---|---|
| **P1** | 200A | 200A | 180[a] | 180A | 160A |
| **P2** | 220A | 220A | 200[a] | 180A | 140A |
| **P3** | 220A | 220A | 200[a] | 180A | 140A |
| **P4** | 200A | 200A | 180[a] | 180A | 160A |
| **P5** | 220A | 220A | 200[a] | 180A | 140A |
| **P6** | 240A | 220A | 200[a] | 180A | 140A |
| **P7** | 220A | 220A | 200[a] | 180A | 140A |
| **P8** | 200A | 200A | 180[a] | 180A | 160A |
| **P9** | 200A | 200A | 180[a] | 180A | 160A |
| **P10** | 200A | 200A | 180[a] | 180A | 160A |

Fig. 3 – Plan view of the 3D reference frame with plant asymmetry

The parametric analysis on the values of the critical load parameter is based upon the variation of the length of the beam members (frame spans L1 and L2) between the columns and on the definition of the space geometry of the structure (frame inter-story height H and number of floors with slab L3).

### *3.1. Critical loads evolution associated to span length and inter-story height*

The 3D structure was analyzed with unbraced and braced configurations, the latter using pinned diagonals with null flexural stiffness and with an area of 11 $cm^2$ corresponding to the metallic profiles of series UPN (UPN-80), smaller than the adopted for the beams and columns.

Some results of the critical buckling loads for the 3D frame in Figure 3 (with L1=L2=L) published earlier by Barros and César [2] are herein quickly reviewed in Fig. 4, just for comparison with the ones that will follow in the next paragraph of this article.

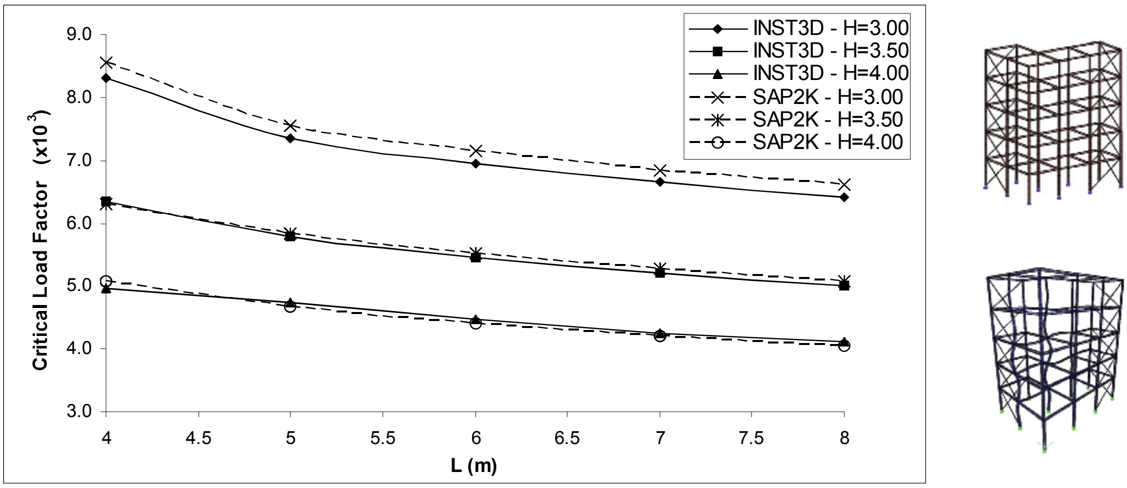



Fig. 4 – Parametric results of critical load factors for the braced frame.

It was verified that the results obtained with the authors INST3D software were always conservative, since they estimate non-linear global carrying capacities (global critical load factors) of this braced asymmetric 3D building frame with values lower than the SAP 2000 results (3-4% lower for H=3 m; much less in the other cases). Moreover both methodologies are close enough, justifying the use of the diaphragm constraint option to model rigid plane diaphragm in SAP 2000.

### *3.2. Critical loads evolution associated to elevation asymmetries*

The critical buckling loads of the 3D building frame initially represented in Figure 3 are now determined but associated with an additional variation – the elevation asymmetry – due to the inclusion of the rigid diaphragm slab L3 solely in a certain number of floors. The parametric study also includes varying the span between columns (L) and the inter-story height (H). The six parametric cases of elevation asymmetry represented in Figure 5 were considered by Cesar [9] and Cesar and Barros [10], in unbraced and braced configurations.

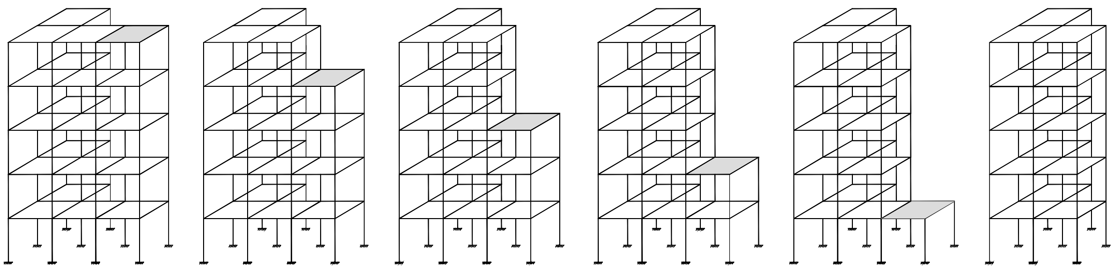


Fig. 5 – Six parametric cases using slab L3, to ascertain effects of elevation asymmetry.

The deformation of each parametric case (Figure 6) typically shows differentiated behavior that allows identifying the structure ruin pattern.

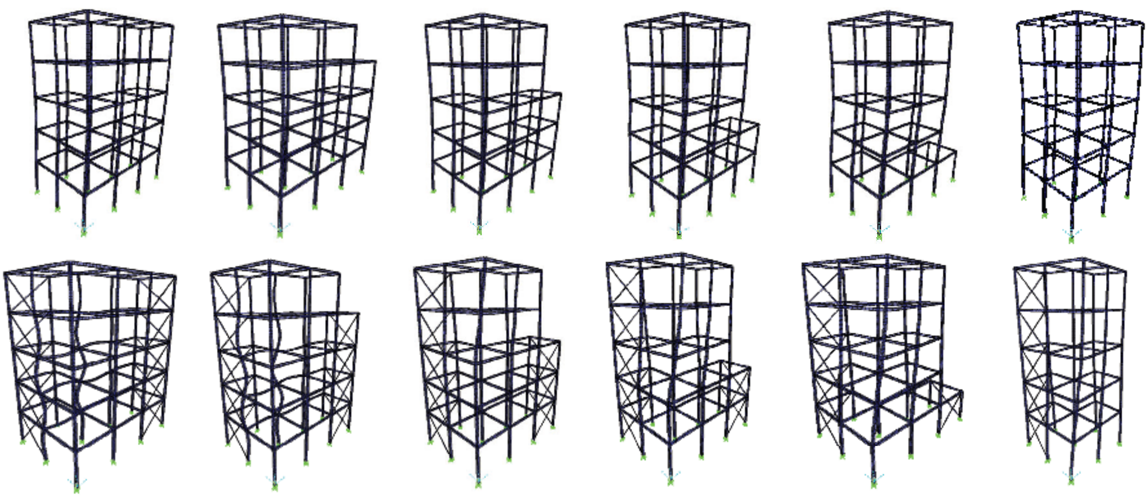


Fig. 6 – Deformed shape for several asymmetric configurations

For the unbraced 3D building frame, the loss of stability occurs for a deformation pattern in the direction of smaller inertia, with translation and rotation of the rigid slab diaphragms as a displaceable joints frame.

The use of the rigid slabs L3 induces a stabilizing stiffening effect up to 2 floors by increasing the rigidity in the direction of the smaller inertia of the columns, therefore insuring an initial slight increase of carrying capacity; however as the rigid slabs L3 are further used in elevation, the 3D tall building character of a displaceable joints frame occurs and the carrying capacity is controlled by the sidesway free configuration of the unbraced 3D building frame.

Some significant results have been graphically synthesized in Figures 7, 8 and 9, comparing the evolution of critical buckling loads of the six elevation asymmetry cases, unbraced and braced, for the mentioned parametric study.

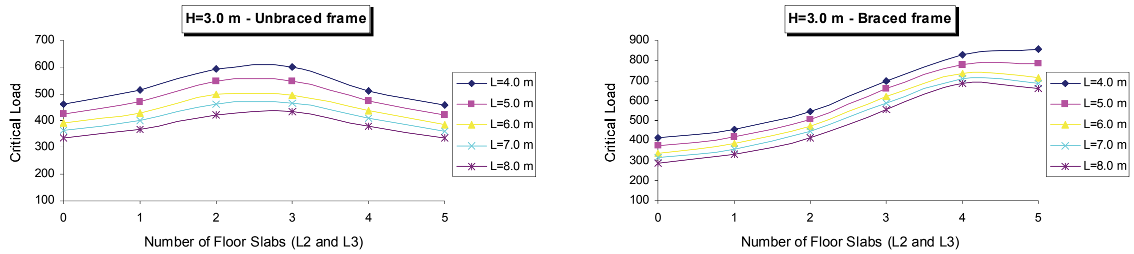



Fig. 7 – Parametric cases using slab L3, to ascertain elevation asymmetry (H=3.0m)

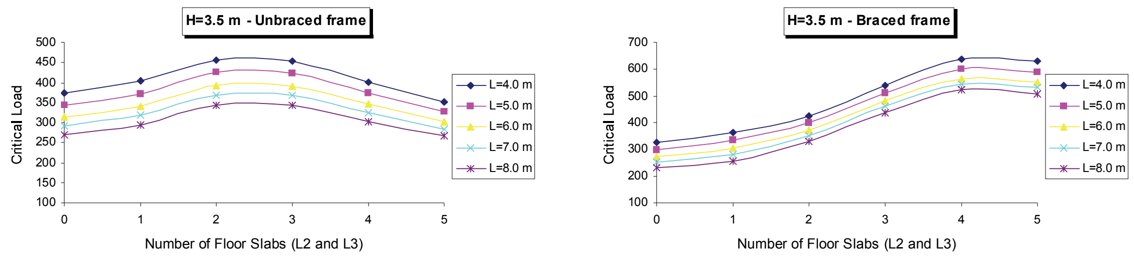



Fig. 8 – Parametric cases using slab L3, to ascertain elevation asymmetry (H=3.5m)

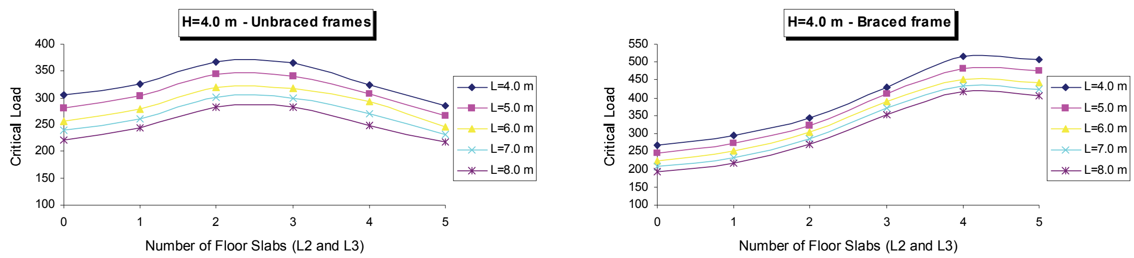



Fig. 9 – Parametric cases using slab L3, to ascertain elevation asymmetry (H=4.0m)

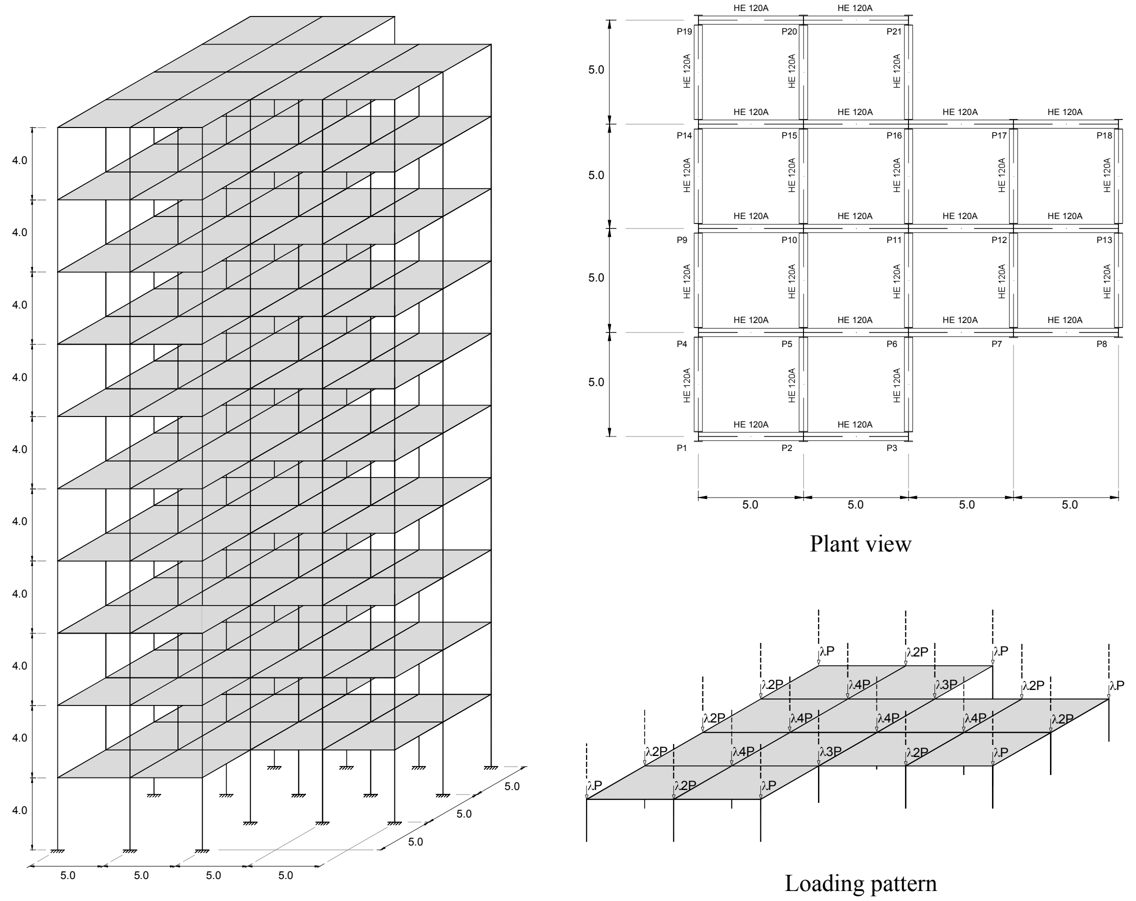
The elevation asymmetry plays a very important role in the parametric study, since the number of floors with the rigid diaphragm slab L3 significantly changes the non-linear geometric carrying capacity of the 3D reference frame.

For unbraced configurations, it is verified that the value of the critical buckling load increases with the number of floors with rigid slabs L3, reaching a maximum value for 2 slab floors; for 3 rigid slab floors the carrying capacity is practically of the same value, but when more than 3 rigid slab floors are used along height a loss of the carrying capacity is observed.

For braced configurations, a continuous increase of the critical buckling load with the number of floors with rigid slabs L3 is distinctively observed: the carrying capacity practically doubles, for the range of parametric studies analyzed.

*3.3. Second-order behavior of an asymmetric 10 floors building*

In this case the analyzed structure, shown in Figure 10, is a 3D building frame with 10 floors and geometric asymmetry in plan along one direction.




Plant view

Loading pattern

Fig. 10 – Perspective and plan view of 3D building frame and loading pattern

The parametric study of this 10 floor asymmetric building frame will not be made for span (L) and inter-story height (H) variations, but will access the influence of the brace elements position in order to increase structure performance

The 3D building frame was pre-designed considering the actions mentioned in the RSA (Portuguese regulatory code for actions), consisting of:

- Self weight (a 20 cm solid concrete slab increased by 10% to add beam self-weight);
- Live load (Floors: 2,0 kN/m$^2$, Roof : 1,0 kN/m$^2$);
- Remaining permanent loads and dividing walls (Floors: 2,5 kN/m$^2$, Roof: 1,5 kN/m$^2$).

The combination of actions used ($S_d$ = 1,35 G + 1,50 Q) to design the resisting structural elements (columns and beams) is also referred in the Portuguese regulatory code (RSA).

The process was initiated determining the critical parameter and the instability mode for the 3D frame without bracing elements, repeating the process for the braced structure.

Two bracing schemes were used (Figure 11), the first one consisting in inserting bracings in the weaker 2D frames along the minor inertia direction and the second one consisting in inserting bracings in all corners trying to guarantee equal frame behavior along two axes.

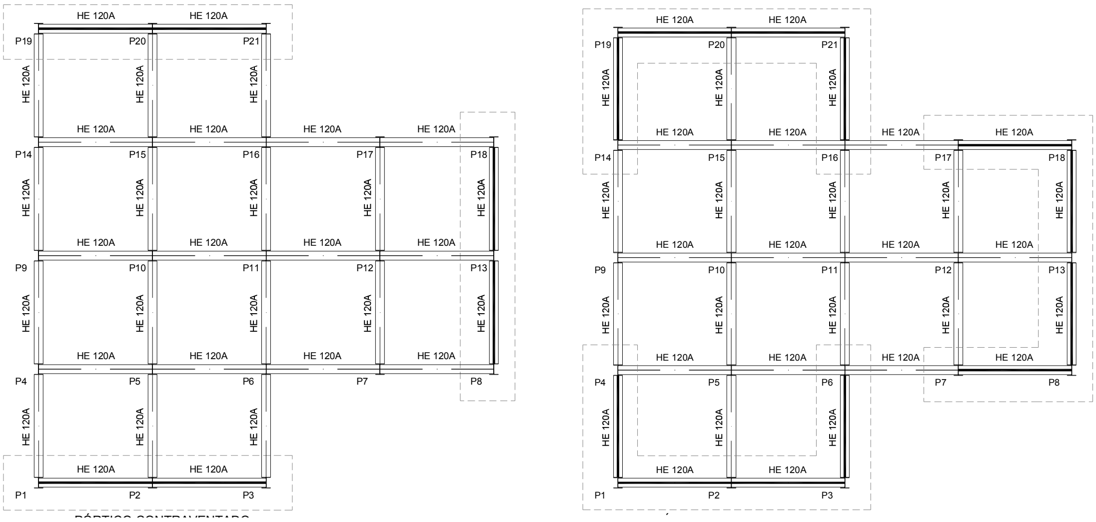
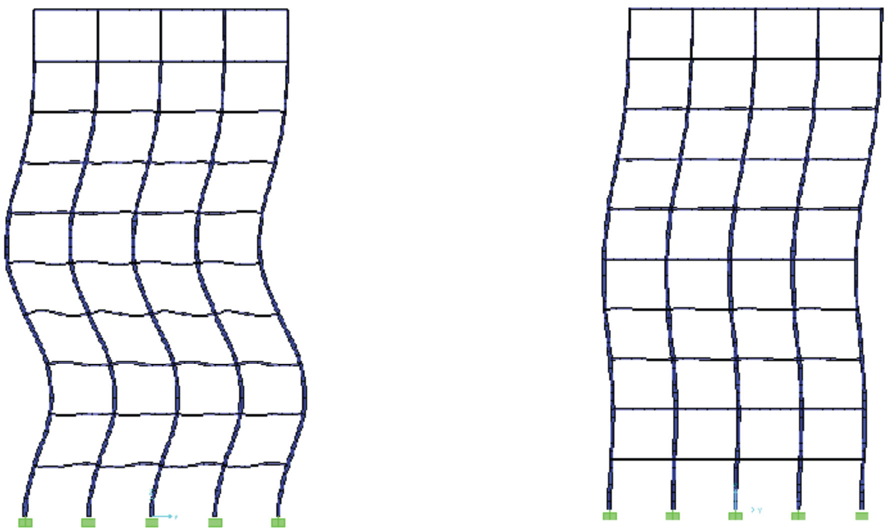



Fig. 11 – Plan view of the 10 floor 3D asymmetric building with bracing schemes

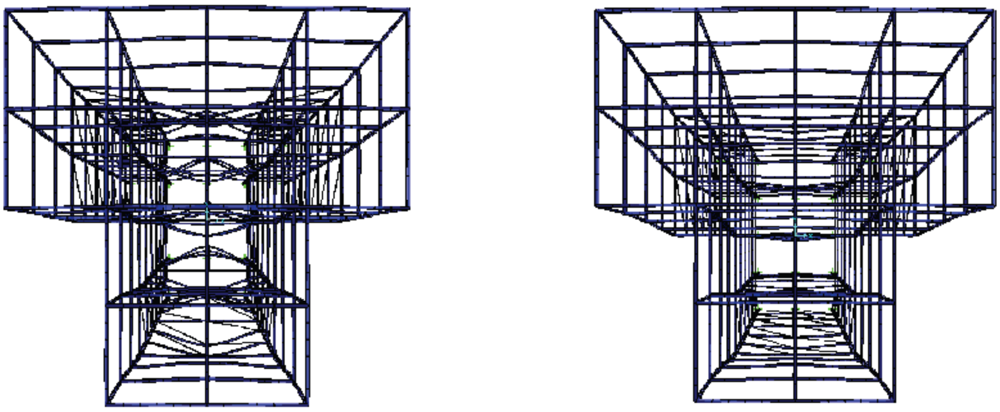
For the unbraced structure, the critical load factor obtained was λ=81,46. Using the first bracing system scheme in all 10 floors along the height, ensures an increase of the carrying capacity characterized by a critical load factor of λ=119,59.

The initial analysis contemplated inserting bracing elements in all floors, and then systematically eliminate some starting from the upper floor until the first floor, to ascertain the number of floors with bracing elements that would influence the carrying capacity (Figs. 12-13). For each configuration, i.e. number of floors with bracing elements, a new calculation was made.



3 bracing floors eliminated (from top) | 4 bracing floors eliminated (from top)

Fig. 12 – Deformation of central 2D frame for several bracing floors configurations, associated with first bracing scheme along weaker peripheral frames



3 bracing floors eliminated (from top) 4 bracing floors eliminated (from top)

Fig. 13 – Plan view of the deformation of the 3D building frame for two bracing floors configurations, associated with first bracing scheme along weaker peripheral frames

For the second bracing system scheme represented in Figure 11 applied in all 10 floors along the height, the carrying capacity increases significantly ($\lambda$=159,54) when compared with the carrying capacity of the first bracing system scheme ($\lambda$=119,59). Such carrying capacity is almost twice of the value associated with the unbraced frame ($\lambda$=81,46).

Eliminating bracing elements in the upper 4 floors, decreases slightly the carrying capacity since the critical load factor is now ($\lambda$=151,55); such decrease is more significant when bracings from the upper 5 floors are eliminated, for which the critical load factor is now ($\lambda$=132,56). The reduction can be associated with the instability mode shape of the structure as a sway frame. When bracing elements from the upper 3 floors are eliminated, the structure shows a non-sway deformation; the suppression of the bracing elements from the upper 4 floors, corresponds to a partial sway deformation; when removing bracing elements from the upper 5 floors, the structure no longer presents a non-sway behavior, showing nodal translations at each floor level where the diagonal elements have been removed (Figure 14).

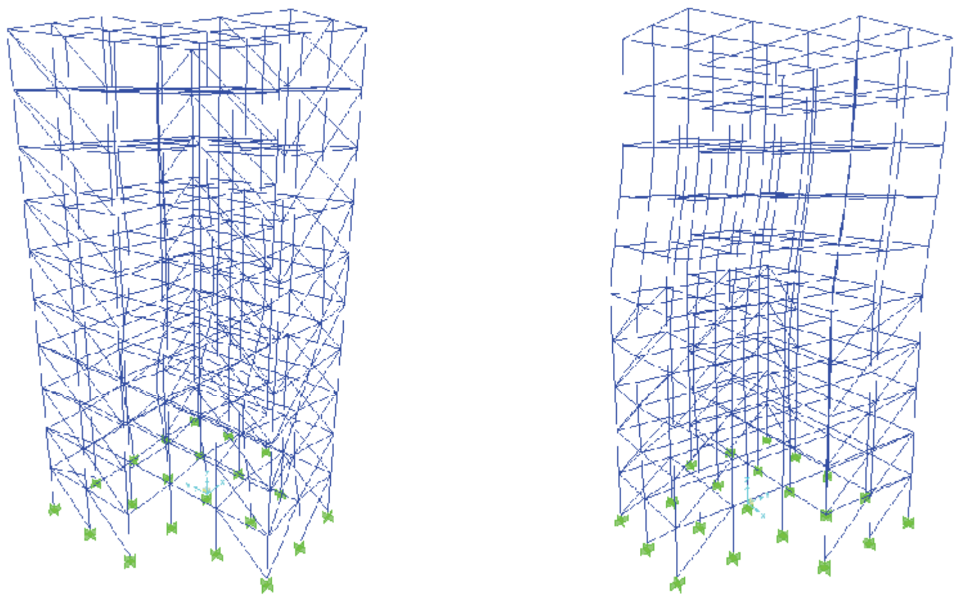


Fig. 14 – 3D deformation patterns for two bracing floors configurations

When bracing elements are introduced the overall global structural behavior changed, concluding that their use controls significantly the asymmetric structure carrying capacity and structural performance.

The bracing system for this asymmetric 3D frame, either along two planes in the peripheral frames or in the corners planes of the building, is the technical and efficient way to guarantee the increase of the carrying capacity of the structure.

### *3.4. EC3 design code criteria*

Finally the EC3 serviceability criteria must be verified. Table 1 presents the necessary drift verifications relative to the 5 floor 3D asymmetric building frame.

| H (m) | L (m) | δa,x,máx | δs,x | ELS | ELS |
|---|---|---|---|---|---|
| 3 | 4 | 0.0000269 | 0.0084 | H/111524 | H/476 |
| | 5 | 0.0000320 | 0.0089 | H/93750 | H/565 |
| | 6 | 0.0000443 | 0.0093 | H/67720 | H/645 |
| | 7 | 0.0000609 | 0.0098 | H/49261 | H/718 |
| | 8 | 0.0000774 | 0.0102 | H/38760 | H/784 |
| 3.5 | 4 | 0.0000281 | 0.0100 | H/124555 | H/400 |
| | 5 | 0.0000309 | 0.0106 | H/113269 | H/472 |
| | 6 | 0.0000337 | 0.0112 | H/103858 | H/536 |
| | 7 | 0.0000441 | 0.0117 | H/79365 | H/598 |
| | 8 | 0.0000544 | 0.0122 | H/64338 | H/656 |
| 4 | 4 | 0.0000295 | 0.0110 | H/135593 | H/364 |
| | 5 | 0.0000299 | 0.0121 | H/133779 | H/413 |
| | 6 | 0.0000304 | 0.0132 | H/131579 | H/455 |
| | 7 | 0.0000358 | 0.0138 | H/111732 | H/509 |
| | 8 | 0.0000412 | 0.0143 | H/97087 | H/559 |

Table 1 – Verification of EC3 serviceability criteria

The EC3 serviceability criteria are verified, since the limiting lateral drift displacements of H/300 are never reached. These verifications were also made for the 10 floor 3D asymmetric building frame, ensuring the validity of EC3 regulatory dispositions with respect to the allowable serviceability limits on lateral drift.

### 3. Conclusions

For the asymmetric 3D building frame, the results obtained with the authors INST3D software with exact total stiffness formulation were always conservative as compared with other software results.

For the elevation asymmetry case, increasing the number of rigid slabs may not necessarily imply an increase of the carrying capacity of the structure, if the 3D asymmetric structure is of the type of displaceable joints sidesway free building frame. Such increase in carrying capacity can only be verified for un-displaceable joints sidesway prevented structures.

For the efficiently braced 3D building frame, the stabilizing stiffening effect of the rigid slabs L3 insures a continuous increase of carrying capacity; this stiffening effect is more effective for bracing located in the lower stories.

The behavior of the 5 floor asymmetric 3D building frame is controlled by the 2D frame that presents greater carrying capacity. In this case the frame presents a behavior of the type of un-displaceable joints sidesway prevented structure.

If the 3D asymmetric tall structure has elevated zones, the configuration of these substructures may condition the global carrying capacity. The carrying capacity of these elevated zones is crucial for the overall performance of the structure, especially if it is of the unbraced displaceable joints sidesway free type. The configuration that insures a better geometric non-linear behaviour and carrying capacity usually emphasizes a pyramidal elevation layout.

With the 10 floor structure it was verified that there's no need to introduce bracing elements in all floors to ensure overall stability.

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