Koce Todorov
PhD, Associate Professor
University "Ss. Cyril and Methodius"
Faculty of Civil Engineering – Skopje
todorov@gf.ukim.edu.mk

Ljupco Lazarov
PhD, Full Professor
University "Ss. Cyril and Methodius"
Faculty of Civil Engineering – Skopje
lazarov@gf.ukim.edu.mk

DISPLACEMENT DISTRIBUTION INDEX AS A TOOL FOR IDENTIFICATION OF VERTICAL IRREGULARITY OF STRUCTURES

Vertical regularity plays an important role in the behavior of structures exposed to seismic action. The structure can be classified as regular if it meets certain prescribed requirements, which are usually explicitly defined in the seismic design codes. In this paper, the vertical irregularity of structures has been identified through the ratio between the maximum inter-story drift and maximum roof drift. In order to quantify this relationship, regardless of the number of stories, the parameter named as index for distribution of displacement at height (DDH) has been defined. Evaluation of the proposed index has been done through an extensive incremental dynamic analysis of six masonry infilled reinforced concrete frames with open first story. Obtained results shows that this index can be used as an indicator for the detection of structural potential to go into the unfavorable failure mechanism.

Keywords: vertical irregularity, displacement distribution index, masonry infill

1. INTRODUCTION

Building structures with irregular distribution of mass, stiffness, strength and geometry along building height may be classified in the group of structures with vertical irregularities. Vertical irregularity is manifested by the appearance of two effects: weak story and soft story. The term week story is used when lateral strength of one story is less than lateral strength of the story above, while the term soft story is defined to exist where there is a story in which the lateral stiffness is less than the stiffness in the story above. During the strong earthquakes, such an irregular stiffness and strength configuration may result with the concentration of lateral deformations at the level of a single story, which may lead to an undesirable soft story failure mechanism, Figure 1. Many building structures having soft story, suffered major structural damage and collapsed in the recent earthquakes. Large open areas with less infill and exterior walls in ground floor compared to upper floors are the cause of damages. In such buildings, the stiffness of the lateral load resisting systems at those stories is quite less than the stories above or below [5,6,7].

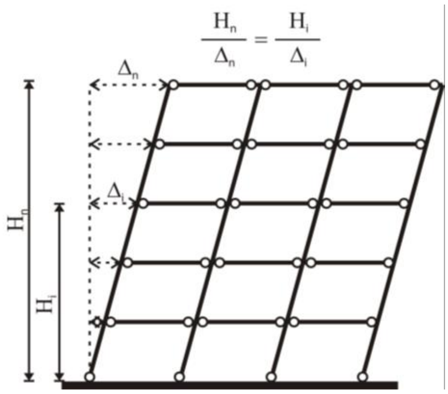
Figure 1. Soft-story mechanism in the ground floor

There are many variable parameters and constructional features that affect regularity and therefore it is quite difficult to characterize whether a structure is regular or irregular [2,8]. An additional impact on the degree of irregularity amplification may also be caused by non-structural elements such as infill walls, whose impact is often neglected in the process of analysis and design.

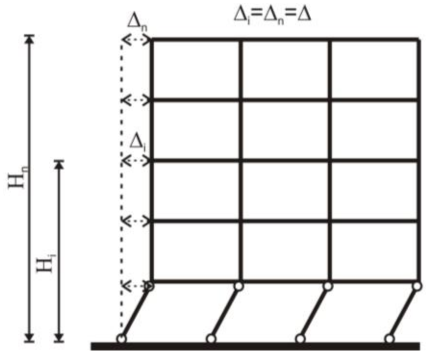
Taking into account the above facts, the codes for design of seismic resistant structures define different levels of design seismic forces, depending on whether the prescribed vertical regularity criteria are met. According to the applicable Rulebook in our country, Rulebook on technical norms for construction of buildings in seismic areas [4], structures with flexible story, i.e. with a sharp change of stiffness in height, are designed for double greater seismic lateral force compared to regular structures. Although such a provision exists, the Rulebook does not have an objective criterion for classification of structures as a flexible story structure. According to EN1998-1 [1,3] structures that do not meet the vertical regularity criteria are designed with a 20% reduced behavior factor value, resulting in a 1.25 times greater design seismic forces compared to regular structures. Although there are criteria for vertical irregularity in EN1998-1, some of them are subjective in nature.

2. INDEX FOR DISTRIBUTION OF DISPLACEMENT AT HEIGHT

The displacements at the top of the structure represent a global measure of the degree of deformation which can be close related with the degree of structural damage. The limit values of the total displacements which correspond to a certain degree of damage, depends on the distribution of the displacements by height. For a multi-story structure, peak top displacement in the range of 0.2% from the total height may represent an insignificant degree of damage, if the inter-story drifts are uniformly distributed along the height, Figure 2a) or they can be an indicator of serious damage, if the inter-story drifts are concentrated at one story level, Figure 2b).



a) beam sway mechanism of failure



b) soft story mechanism of failure

Figure 2. Soft-story mechanism in the ground floor

The ratio between maximal inter-story drift $maxISD=(\Delta_i-\Delta_{i-1})_{max}/h_i$ and maximal top drift $maxTD=d_n/H_n$ can be a good indicator of damage distribution along the building height. In order to quantify this relationship, regardless of the number of storeys (n), the parameter named as index for distribution of displacement at height (DDH) with the boundary values from 0 to 1 was defined, Equation 1.

$$DDH = \frac{\frac{\max ISD}{\max TD} - 1}{n-1} \tag{1}$$

For the same values of maxISD and maxTD, which implies a triangular distribution of displacement, or formation on beam sway mechanism, the value of this index is close to 0. Higher values of this index (close to 1) indicate a concentration of inter-story drift on one story level, which is characteristic for the formation of soft story mechanism.

3. EVALUATION OF PROPOSED INDEX FOR MASONARY INFILED FRAMES WITH OPEN FIRST STORY

The proposed index for distribution of displacement at height was evaluated through an extensive nonlinear dynamic analysis. Six reinforced concrete frames with different number of story (n=2, 3, 5, 7, 10 and 13) in the following text marked as frames R1, R2, R3, R4, R5 and R6 were analyzed. All analyzed structures are designed as three bay plane frames with a span of 5m and a constant story height of 3m. In the phase of assessment, all frames were additionally upgraded with the presence of masonry infill panels in all spans and stores, except for the first one. Masonry infill was defined with two different strength and stiffness characteristics, namely week infill (WI) and strong infill (SI). All frames were exposed to twenty-one different earthquake ground motions, grouped into three groups of 7 records. All selected records were scaled to ten different amplitudes, based on scaling of pick ground acceleration [6,7].

3.1 TOP DISPLACMENT V.S. INTERSTORY DRIFT RATIO

The relationship between the maximal inter-story drifts (maxISD) and the maximal top drifts (maxTD) for the sixth analyzed frames obtained with the individual records from the three groups of earthquakes scaled to ten levels of peak ground acceleration are presented at Figure 3. From the presented diagrams, a nearly linear tendency of this relationship can be noticed. The largest deviations are observed at the bare frames (BF) and usually are result of earthquakes records from the first group, which contains registrations of earthquakes with a dominant frequency range of low periods.

In infilled frames R1 and R2, as well as the frame R3 with strong infill, there are almost no deviations from the linear relationship, which is due to the concentration of displacements at the level of the first story. In the higher infilled frames, the ratio between the maximal top drift and maximal inter-story drift is greater, indicating a more uniform distribution of the displacements in height. With increasing of the displacements, this ratio decreases, indicating a concentration of damages on separate floors. For frames R1 and R2 with weak and strong infill the ratio maxTD - maxISD is almost identical, indicating a slight influence on the characteristics of the infill on the distribution of displacements. In the higher frames with a strong infill this ratio is lower, indicating the concentration of displacements at the level of one (in the case of frames R1, R2 and R3) or at the level of several floors (in frames R4, R5 and R5) of the considered structures.

The change of the DDH index, in the function of the peak ground acceleration, for the analyzed frames, exposed on the individual records from the second and third group of earthquakes is presented at Figure 4.

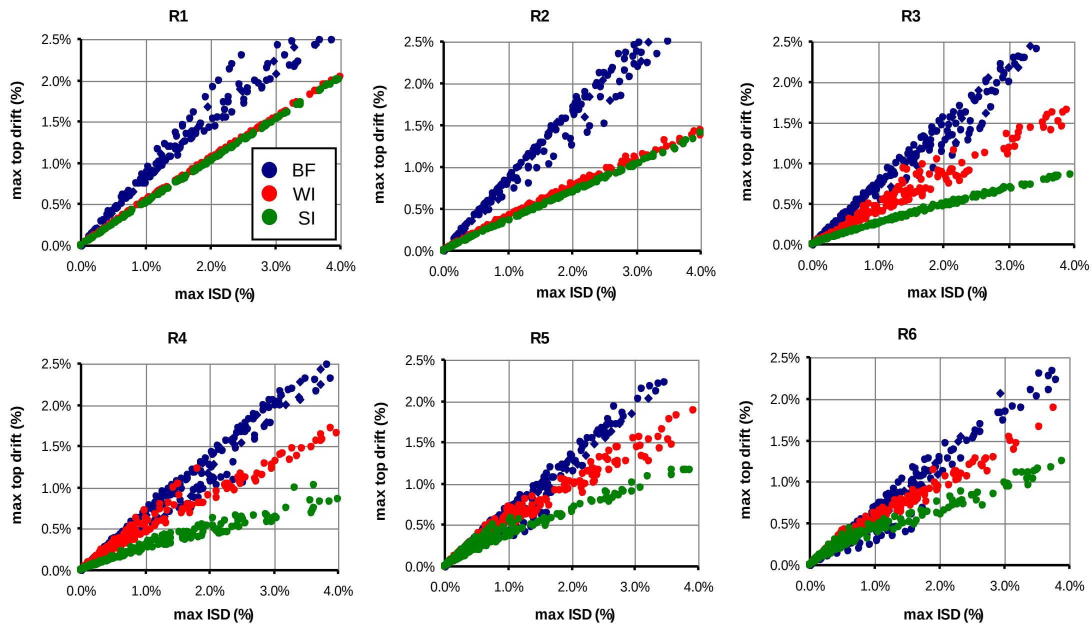


Figure 3. Ratio between the maximal inter-story drifts (maxISD) and the maximal top drifts (maxTD) of the analyzed frames

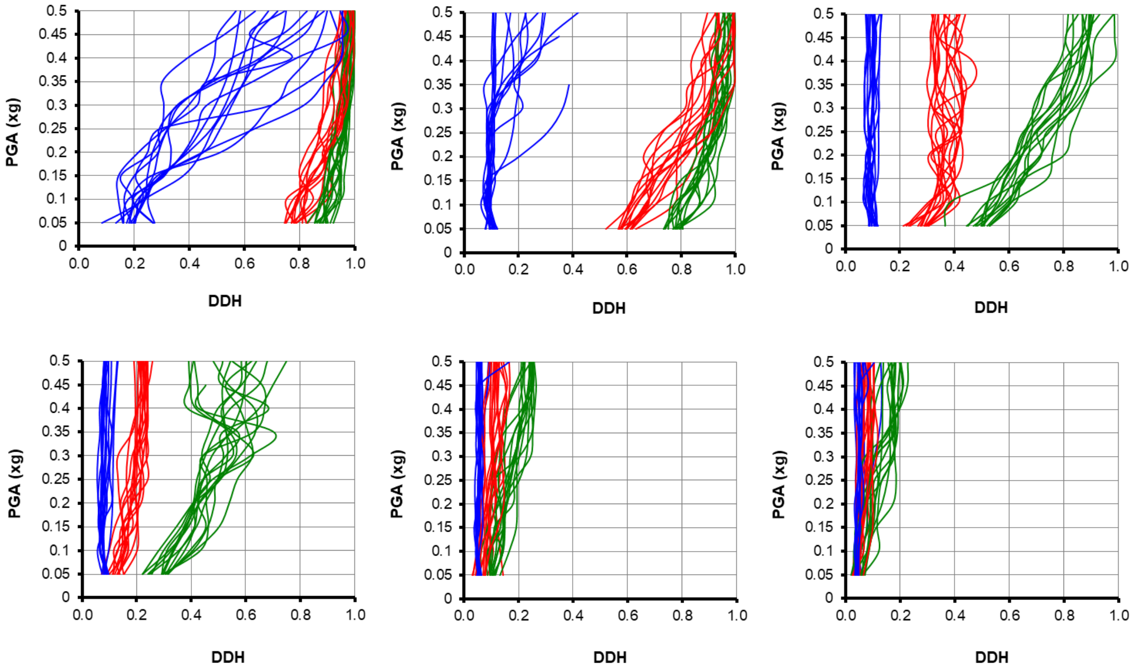


Figure 4. DDH index in function of PGA for analyzed frames

4. CONCLUSIONS

The ratio between maximal inter-story drift and maximal top drift can be a good indicator for the distribution of damages by height of the building. For the quantification of this ratio, regardless to the number of stories, an Index for Distribution of Displacement at Height (DDH) was defined. When this index, for low levels of earthquake intensity, is greater than 0.2 to 0.3 a concentration of the relative displacement at the level of one or more stories can be expected. This concentration of displacement can lead to occurrence of a soft story mechanism of failure at higher levels of peak ground acceleration. Although the failure mechanism that can lead to structural collapse is difficult to predict from the results obtained from the linear analysis, this index can be used as a marker-indicator for the detection of structural potential to go into the unfavorable plastic mechanism.

REFERENCES

[1] CEN – European Committee for Standardization (2004), Eurocode 8: Design of structures for earthquake resistance – Part 1. European standard EN 1998–1.

[2] De Stefano M., Pintucchi B. (2008), „A review of research on seismic behavior of irregular building structures since 2002“, Bulletin of Earthquake Engineering, Vol.6, No.2, 2008, pp. 282-308.

[3] Fardis M.N., Carvalho E.C., Fajfar P., Pecker A. (2015), “Seismic design of concrete buildings to Eurocode 8” CRC Press, Taylor & Francis Group, 6000 Broken Sound Parkway NW.

[4] Federal Institute for Standardization (1981), Rulebook on Technical Norms for Construction of Buildings in Seismic Areas, Official gazette of SFRJ, N31, pp. 841-855.

[5] Halde V.V., Deshmukh A.H. (2015), “Review on behavior of soft storey in building”, International Research Journal of Engineering and Technology, Vol.2, Issue:08, November 2015, p.p. 327-329.

[6] Todorov K. (2014),” Seismic Performance of Masonry Infilled Reinforced Concrete Frames with Open First Story“, PhD thesis, Faculty of Civil Engineering, University Ss. Cyril and Methodius, Skopje, R. Macedonia.

[7] Todorov K., Lazarov Lj. (2018), "Nonlinear Static vs. Incremental Dynamic Analysis of Infilled Frames with Open First Floor", Building Materials and Structures 61 (2018) 4, p.p. 3-22.

[8] Varadharajan S., Sehgal V.K., Saini B. (2013), „Review of different structural irregularities in buildings“, Journal of Structural Engineering, Vol. 39, No. 5, December 2012 - January 2013 pp. 393-418 No. 39-51.