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Multi-Scale Damage Assessment of a 1960s Large-Panel Building: Linking Global Damage Grades to Element Limit States

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Abstract

The city of Zagreb had a significant number of large panel buildings constructed in 1960s. Similar typology and technology was implemented in the USA, Soviet Union and China in 1940-60s. Critically, these buildings were built according to outdated seismic codes, leading to complex and potentially dangerous behavior under seismic loading. As a part of the effort to mitigate risks associated with these type of buildings, a comprehensive structural analysis is conducted with the aim of quantifying their seismic resistance and identifying relevant failure mechanisms. One important part of this analysis is developing specialized damage models of building elements and a set of criteria to correlate element damage with expected damage grades of a whole building according to EMS-98. In this paper, a brief overview of a case study numerical model and its calibration is provided. Definition of element damage states is described briefly, with the main focus of the paper being correlation between element damage states and whole buildings damage grade, adapted to be similar to EMS-98 criteria. This correlation is to be programable, to allow automatic diagnostic of a numerical model, enabling a vulnerability analysis through Multiple Stripes Analysis, Incremental Dynamic Analysis or other methodology which requires a large number of ground motions to be considered..

Keywords: Large panel building, Abaqus, ETABS, precast, residential, seismic

1- INTRODUCTION

The city of Zagreb had a significant number of large panel buildings constructed in 1960s (1). Similar typology and technology was implemented in the USA, Soviet Union and China in 1940-60s (2). Critically, these buildings were built according to outdated seismic codes, leading to complex and potentially dangerous behavior under seismic loading (2,3). As a part of the effort to mitigate risks associated with these buildings, a comprehensive structural analysis is conducted with the aim of quantifying their seismic resistance and identifying relevant failure mechanisms. Identification of failure mechanisms can be done in multiple ways, with various degrees of accuracy. One approach is to create a numerical model of the building, able to simulate its seismic response well enough for a time-history analysis, then infer from the model the likely failure mechanisms. When creating this model there are 3 main properties the model needs to have calibrated: strength, stiffness and damage model. This study focuses on the damage aspect of the modelling process. Quantifying the damage of a building can be done in many ways. One of the most effective is a Damage Index (DI). A comprehensive review of the state of the art on damage indices is provided by (4), while a summary is provided here. A damage index is a value assigned to a building quantifying its damage state, typically ranging from 0 to 1. This value can be deduced through various methods, from a range of criteria, it can be deduced from change in structures fundamental period, change in damping, directly or by proxy from damage to individual elements (5), by observing direct material damage (6). If obtained from damage to individual elements, limit states for those elements also need to be defined. Finally, to obtain a damage state, a set of criteria is developed for the structure, correlating the damage index with individual damage states. A similar process is employed when conducting post earthquake surveys of damage to building portfolios, with EMS-98 (7) IMS-25 (8) as examples. In this case an engineer inspects structural elements of a building after an earthquake, estimates their damage state and the overall damage state of the building based on guidelines from the EMS-98 or IMS-25. The aim of this paper is to combine this two approaches. Create a set of criteria for damage states of a building based on EMS-98 framework, establishing a procedure to correlate a global response such as story drift with local damage specific to the structural system of the case study building.

2- CASE STUDY BUILDING

The case study building is one standardized residential building made in 16 instances in the city of Zagreb. As a large panel building it has its walls and floors constructed out of prefabricated reinforced concrete panels, connected by ring beams which are poured in situ. The walls are primarily made of 2 different wall panels, both shown in **Figure 1**. The P1 panel is situated at ends of walls, while the P2 panel is situated between two other panels (see Figure 3). This is also indicated by P2 panels having shear-keys on both sides, while P1 panels have shear keys on one side and vertical rebar on the other side. The vertical rebar on P1 panels is also the only continuous vertical connection in the entire building, aside from tensile strength of concrete. Regarding position of floor panels, it is important to note that most of the floor panels are supported by transverse walls, with the only exception being the walls supporting the staircase (see Figure 2).

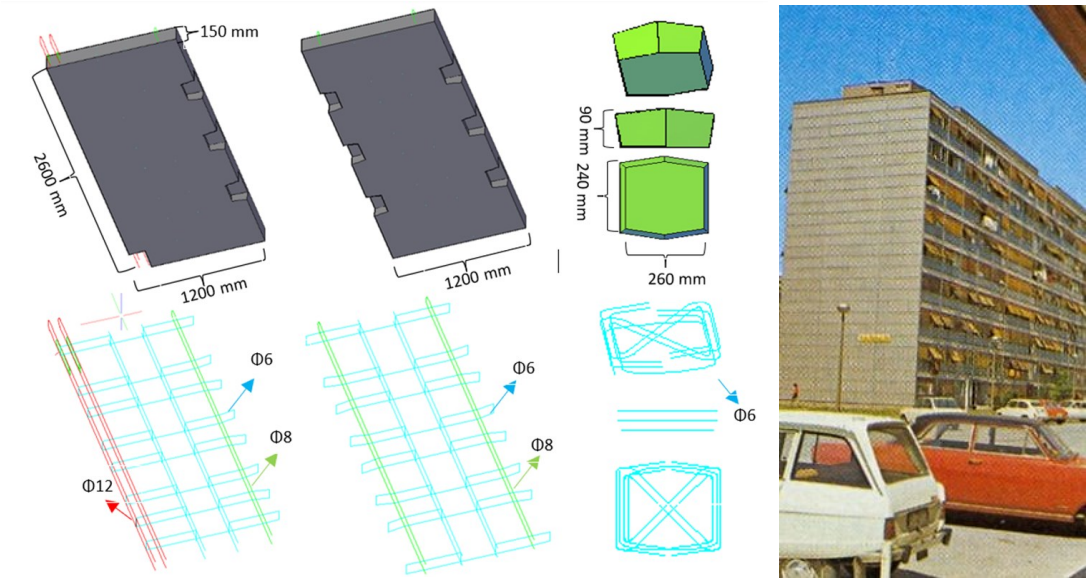


Figure 1 – Wall panel P1 (left) and P2 (right) and the whole building

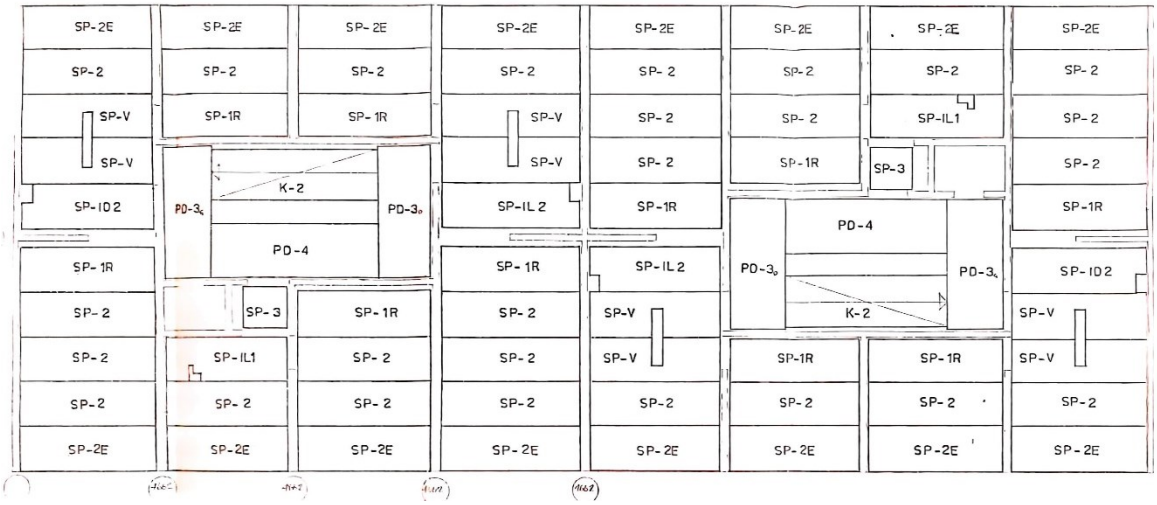


Figure 2 – Typical floor plan of the case study building – floor panels

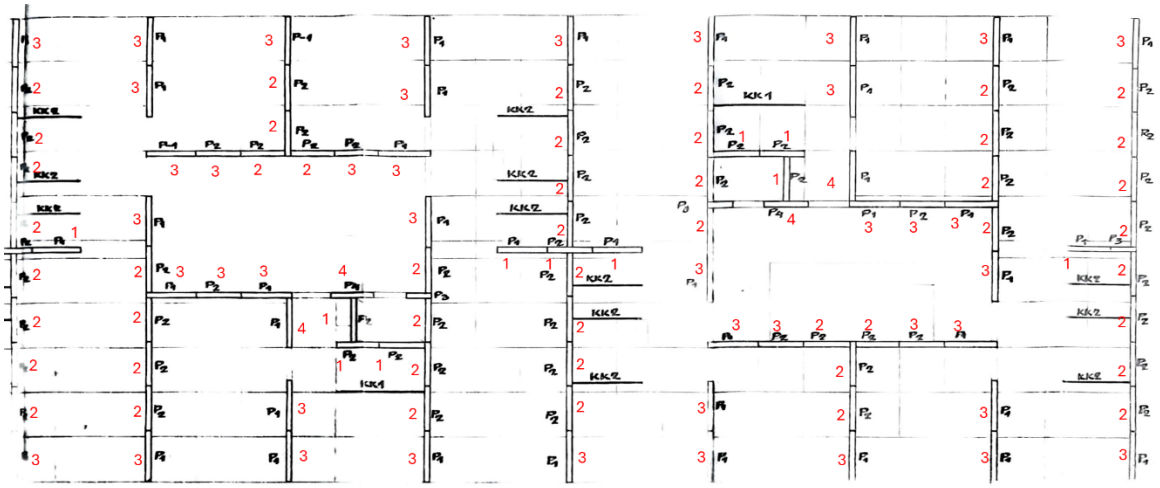


Figure 3 – Typical floor plan of the case study building – wall panels

3- FAILURE MECHANISMS AND MODELLING METHODOLOGY

The connections between precast elements are executed as wet joints with next to no rebar, making failure on the connections between wall panels more likely than failure of the precast panel, leading to a complex failure mechanism. A single wall panel can experience rocking (uplift and toe crushing), shear sliding, and failure of shear-keys. Modelling of this behavior is done in a few steps. Two groups of numerical models are created. One in Abaqus (9) and one in ETABS (10). The Abaqus models are used to investigate behavior of structural details, while the ETABS model is used to model behavior of the whole building. Abaqus numerical models are using 3D volumetric finite elements and Concrete Damage Plasticity constitutive model (11). Rebar is modeled as frame elements embedded in the volumetric finite elements. This high fidelity model is calibrated according to experiments from literature and used to calibrate the simpler ETABS model. This ensures that the model of the completed building has realistic stiffness, strength and failure mechanisms (uplift, toe crushing etc...). A calibration of individual limit states is done separately and is described in the next chapter.

Figure 4 shows models of individual wall panels in both software's. The ETABS model uses lumped plasticity elements to connect individual (elastic) panels. The lumped plasticity elements (links) model the following individual failure mechanisms: AX – toe crushing and uplift (multilinear plastic), SH – shear sliding (friction pendulum), KEY -shear key failure (multilinear plastic). These models are calibrated under various boundary conditions expected in the building. The final model is then assembled of these individual and calibrated panels and is able to model the anticipated failure mechanisms. Finaly, each lumped plasticity element has its own limit states defined through its displacement.

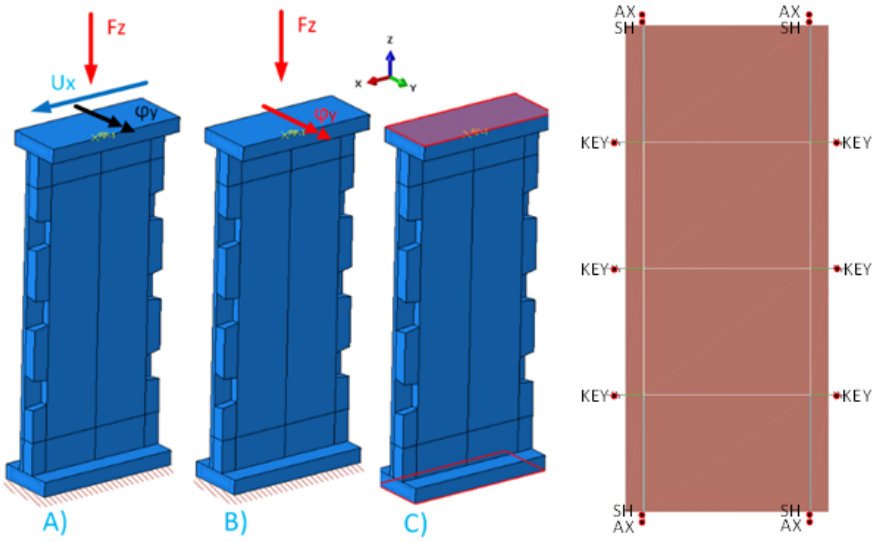


Figure 4 - Models of individual panels in Abaqus (left) and ETABS (right)

4- PRECAST ELEMENT LIMIT STATES

Ensuring correct damage simulation on the ETABS model is done through calibration according to the Abaqus model. Briefly, EMS-98 criteria, along with criteria from literature (12) are applied to the Abaqus model to find drifts and deformations associated with various crack sizes, rebar yielding or other events. Once the ETABS model is calibrated according to the Abaqus model, it is considered that all relevant failure mechanisms can be quantified, or in other words, toe crushing, uplift, shear sliding and shear-key failure can be identified in a global model in ETABS after or during a time-history analysis. There is some expert judgment required, as these criteria change with variation of axial loading of panels, as the failure mode changes, while the values selected in the final ETABS model are fixed. Figure 5 shows an example of results of one such analysis, with panel displacements at various damage limit states shown. It should be noted that ground floor wall panels are axially loaded up to only 10% of their capacity under static load. However, this axial load can change under lateral loading, so axial loading all the way up to 90% is tested. The Figure shows drift levels of a single wall panel, for limit states of ND (no damage), LD (limited damage), SD (significant damage) and NC (near collapse).

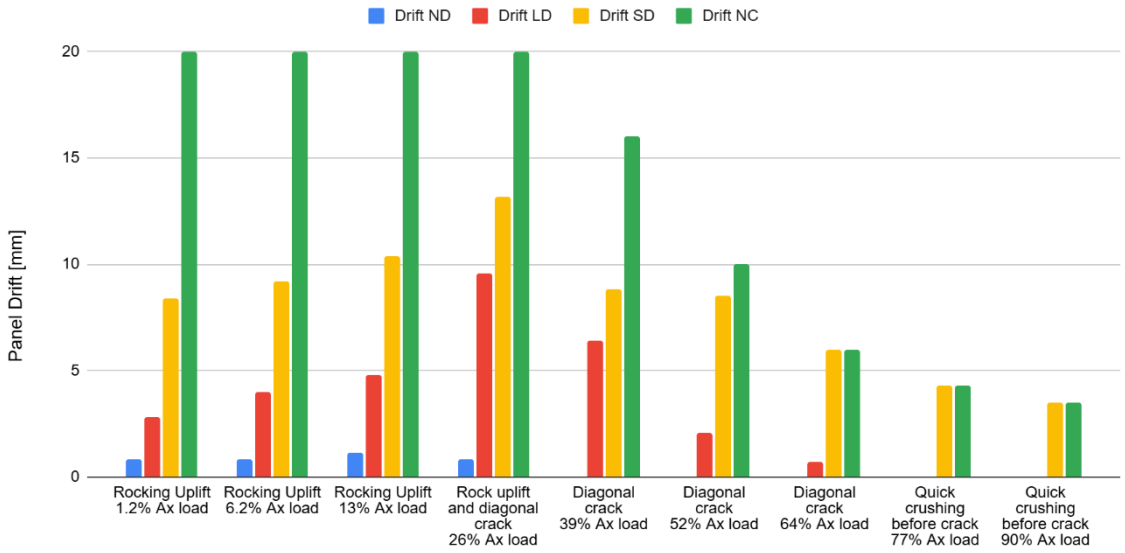


Figure 5 – Results of damage limit analyses for one wall panel

5- GLOBAL DAMAGE STATES AND DAMAGE DISTRIBUTION

With damage to individual precast elements defined through limit states, the main subject of this study needs to be addressed, that is the connection between limit states of individual precast elements and the global damage state of the building. Literature has a somewhat robust process, which could be applied directly. This would however leave some complications with regards to failure mechanisms of this building typology, which could possibly be addressed through extensive modification of weight factors, however this process leads to complications, which can lead to errors. Instead, a modification of the process is presented here. The process of global damage state estimation is conducted in two different and parallel processes, depending on the expected damage state observed. One process will be used for damage states where expected outcome is a damaged building with **no risk of collapse (process 1)**, and another process for damage states where the expected outcome is **local or global collapse (process 2)** of the building. Another way to describe these processes is that one considers high consequence damage states and local collapse mechanisms, while the other considers all damage states and does not consider local collapse or similar effects. Each process will provide damage states for each story of the building, the higher damage grade is selected as relevant for the final result. This process is described graphically on Figure 6, and described in more detail in following paragraphs.

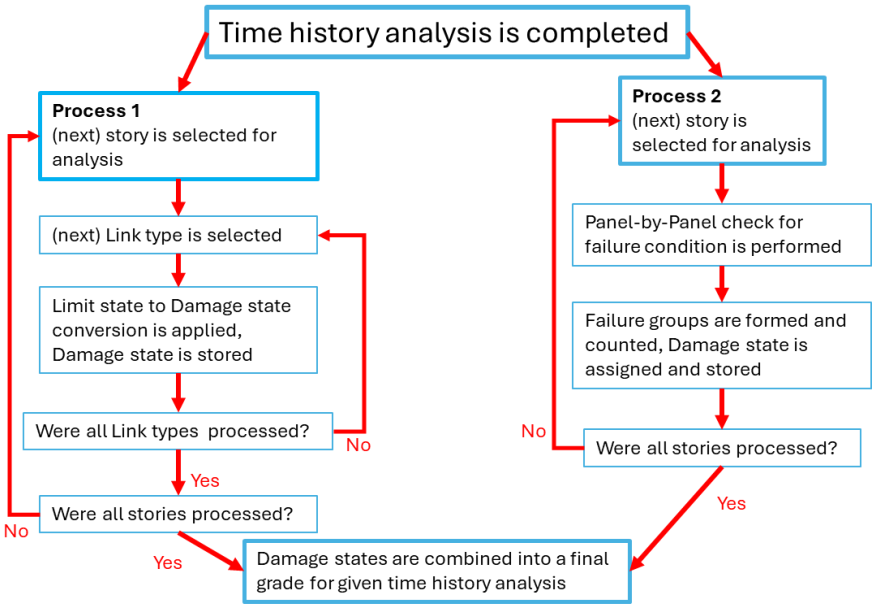


Figure 6 – Flow diagram of damage state estimation for one time-history analysis

Process 1 focuses on quantifying the amount of damage and its distribution. It considers which wall panels failed, and by which failure mechanism while not considering local collapse. Process 1 needs to convert data containing a spatial distribution of wall panel limit states defined by 3 grades (LD – limited damage, SD – significant damage and NC – near collapse) into a single damage state grade, with a range of 1-5. Furthermore, this process needs to distinguish between different failure mechanisms such as uplift, shear sliding, toe crushing and shear-key failure, as each of these failure mechanisms has a different severity of consequences. To accomplish these two tasks, each failure mechanism is assigned a set of **Limit state to Damage state conversion** ranges. Illustrative examples of these ranges are shown in Table 1-Table 4, with visible differences for different failure mechanisms. Quantification of these ranges is discussed in a later paragraph. As the building results are processed, each story is assigned a damage state for each failure mechanism separated by wall orientation (longitudinal or transverse). Each story is assigned an overall damage state based on all failure mechanism damage states and finally, the relevant damage state of the building can be assigned based on individual story states. So to reiterate, after process 1 is complete, every story has a damage state assigned to it (DS1, DS2, DS3, DS4 or DS5), separately for each orientation (longitudinal and transverse), for each failure mechanism (AX, SH and KEY links), and furthermore, a separate damage state is assigned for positive and for negative displacement of each link, in order to distinguish between compressive and tensile failure in AX links. So, an example result may be "Story 1 - AX link - direction X – compression (DS2), tension (DS4)".

Choice of **Limit state to Damage state conversion** ranges is based on a subjective estimate, with an aim to emulate EMS-98 scale and its structural damage to damage state correlation. Limit states as defined for this analysis and described in "Precast element limit states" are directly linked to different types of damage, be it deformation of rebar or concrete crack size or other criteria. It is therefore possible to correlate the damage expected on the building to the limit states of its individual structural elements. In the case of JU-61Z, individual structural elements are considered as individual wall panels, with each panel having a limit state for AX, SH, and KEY link type. Each wall panel has multiple AX, SH and KEY links, each having reached its own limit state. Individual wall panel limit state for AX link type is simply the highest limit state of all AX links of that wall panel, with the same principle used for SH and KEY link types. Therefore, quantification of damage for a individual story is done through counting limit states of individual wall panels, and correlation between wall panel limit states and story damage state is defined through Limit state to Damage state conversion ranges, which define how many elements in certain limit states are required for individual damage states, example ranges are shown in Table 1. These ranges are based on EMS-98 guidelines, including guideline for definition of quantities. Quantities of "few", "many" and "most" are defined as shown in Figure 7.

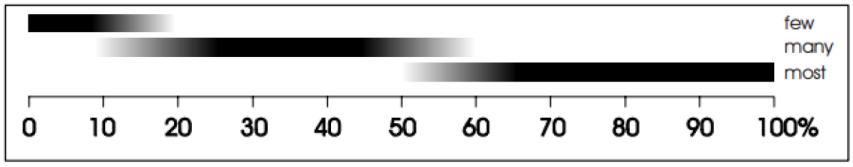


Figure 7 – Definition of quantities according to EMS-98 (7)

In the case of JU-61Z, wall panels have 4 distinct failure mechanisms, shear-key failure, shear sliding, uplift and toe crushing. Each mechanism has its own limit states defined in the ETABS model through displacement limits of lumped plasticity elements (links). This allows independent checks for occurrence of each failure mechanism, enabling consideration of difference in consequences of failure mechanisms. In other words, 10 wall panels with NC limit state for toe crushing leads to a different outcome to 10 wall panels with NC limit state for shear keys. The shear-key failure leads to a reduction in lateral stiffness of the building, with no immediate risk of collapse. Consequently, any limit state of shear-keys cannot trigger DS4 or DS5, the maximum damage state shear keys can trigger is DS3, and this is reflected in the example Table 4. Shear sliding, is another relatively safe failure mechanism. Likely outcomes are minor damage, major but safe displacement of the story leading to inability to repair the building. For shear sliding to become dangerous, the sliding distance should be over 10 cm, to allow one of the transverse walls to fall over the edge of the building, or more likely be damaged due to stress concentrations caused by extreme eccentricity of axial forces. This is reflected in Table 3. Uplift, aside from being able to cause dynamic closing of the horizontal and subsequent compressive damage, is a safe failure mechanism, leading to rebar yielding and a need for minor to extensive repairs, but does not lead to collapse. This is reflected in Table 2, and the highest available damage state being DS4. The final mechanism, toe crushing, can have significant consequences by leading to axial failure of the wall panel. Subsequently, NC limit state can have a more significant effect in Table 1.

Table 1- Limit state to damage state conversion example table – Axial link – compression (AX)

Damage state	LD	SD	NC	LD [%]	SD [%]	NC [%]
DS1	Few	None	None	0-15	0	0
DS2	Many or most	Few	None	15-100	0-15	0
DS3	-	Many	None	0-100	15-55	0
DS4	-	Most	Few	0-100	55-100	0-15
DS5	-	-	Many or most	0-100	0-100	15-100

Table 2- Limit state to damage state conversion example table – Axial link – tension (AX)

Damage state	LD	SD	NC	LD [%]	SD [%]	NC [%]
DS1	Few	None	None	0-15	0	0
DS2	Many or most	Few	None	15-100	0-15	0
DS3	-	Many	None	0-100	15-55	0
DS4	-	Most	Few or many	0-100	55-100	0-55
DS5	-	-	Most	0-100	0-100	55-100

Table 3- Limit state to damage state conversion example table – Shear sliding link (SH)

Damage state	LD	SD	NC	LD [%]	SD [%]	NC [%]
DS1	Few	None	None	0-15	0-15	0
DS2	Many	Few	None	15-55	0-15	0
DS3	-	Many or most	Few	0-100	15-100	0-15
DS4	-		Many or most	0-100	0-100	15-100
DS5	-	-	-	-	-	-

Table 4- Limit state to damage state conversion example table – Shear key link (KEY)

Damage state	LD	SD	NC	LD [%]	SD [%]	NC [%]
DS1	Many	Few	None	0-55	0-15	0
DS2	-	Many or most	Few	0-100	15-100	0-15
DS3	-		Many or most	0-100	0-100	15-100
DS4	-	-	-	-	-	-
DS5	-	-	-	-	-	-

In summary, process **1** will assign each story a damage state, based on each failure mechanism separately, then allowing for a combination of damage states and stories in a later step, producing the final damage state of the building. This process will however not consider possibility of local collapse due to a concentration of NC limit states, this is done separately in the previously referred **process 2**.

Check of potential local failure mechanisms is conducted as a separate process of assigning damage states, referenced previously as **process 2**. This process does not provide information about DS1, DS2 or DS3, it can only provide information about potential DS4 and DS5, and it only checks for failure of wall panels under compression. Based on **Figure 2** it can be concluded that some panels are more critical in transferring axial loading from floor panels. Based on expected consequences of axial failure, each panel is given an importance grade. This grade can be 1, 2, 3 and 4, distributed as shown in Figure 3. Grade 1 means that the panel can fail

with no significant consequences. For grades 2, 3 and 4 a concept of neighboring panels is introduced. Each panel has between 0 and 2 panels attached to it, forming a sort of "group". These groups are used for failure analysis in the following way. A panel with grade 2 is not critical, however, a larger scale failure could lead to local failure of floor panels. A criteria is adopted that every grade 2 can have a maximum of 2 failures in its local group. So out of the grade 2 panel and its 2 neighbors, 2 can fail with no consequence, if 3 fail, this triggers a "local failure". Similarly, a grade 3 panel is simply less redundant, allowing only 1 failure in its local group. This grade is assigned to panels at ends of transverse walls and on staircases. Finally, grade 4 is assigned to certain individual panels, which do not have nearby elements available and provide redundancy. Should a grade 4 element fail, it triggers a "local failure" on its own. If there is 1 "local failure" detected on the story level, this triggers DS4, if there is more than 1 local failure detected, this triggers DS5. Exceptions can be made for walls that are critical for evacuation, such as walls around the staircase, where even one local failure can have very severe consequences, and subsequently, can trigger DS5 with only 1 local failure.
Additionally, establishing local damage distribution allows quantification of damage to individual walls, aggregating damage to wall panels of that wall into one damage grade. This would allow a relatively simple identification of critical walls with regards to collapse prevention and with regards to damage distribution of lower consequence damage. Importantly, the damage estimation shown in "Global damage states" can be applied directly to any group of wall panels. It is therefore possible to apply the same process on a wall-by-wall basis, instead of story-by-story basis, resulting in assignments of damage states to individual walls. Each wall can also be disaggregated to its individual stories to better illustrate damage distribution. A similar approach is used in (5), where a somewhat similar approach is used to characterize damage distribution in URM buildings.

6- DISCUSSION – GLOBAL DAMAGE STATE

The described process 1 and process 2 have significant steps where a subjective engineering estimate is used. In the case of process 1 this step is the choice of limit state to damage state conversion tables. EMS-98 provides a guideline for damage estimation, with quantities such as "few, most, many" elements developing fine cracks, larger cracks, failing entirely etc... the issue being the nature of failure mechanisms of the observed large panel building. As an example, shear-keys failing all the way to NC limit state would leave large cracks in structural elements, in line with damage state 4, however the effects on the structure should not exceed damage state 3, as only structural stiffness would be affected, with no risk of local or global collapse. Similarly, uplift and shear sliding reaching a NC limit state will have lower consequences than toe crushing reaching NC limit state. This is considered through modification of conversion tables for individual failure mechanisms. While this step introduces some lack of precision due to its subjective nature, this step only provides information about existence of damage, not about occupants safety. When observing occupant safety, process 2 should be considered. The subjective portion of the estimate is the choice of consequences for failure of individual wall panels, or in other words, the assignment of an importance grade to each panel. Ideally, a complete analysis of possible local mechanisms would be conducted, considering the load bearing capacity of horizontal ring beams, and force redistribution following compressive failure of groups of wall panels. This would provide a more complex but also more precise insight into possible local failure mechanisms, but is also quite complex and time consuming. Therefore, a simpler approach with importance grades is used to estimate consequences of individual panels losing axial load bearing capacity through extensive toe crushing.
Finally, the global damage state should be considered. DS4 and DS5 are relatively simple, with process 2 defining local collapse, DS4 and DS5 are triggered automatically for the entire structure, regardless of other damage. In the case of DS1, DS2 and DS3 it can be argued that the global damage state of the building should reflect the worst damage state of an individual story, or that it should be a sort of weighted average of damage states from all stories. The reason behind this is that lower damage states offer information about damage existence and distribution, so assigning a whole building DS3, while only 1 out of 10 stories has reached DS3 can be misrepresentative. On the other hand, with onset of collapse and higher damage states, it only takes failure of one story to trigger a wider collapse, meaning that considering the highest story damage grade as the relevant damage grade would be consistent with damage estimation for DS4 and DS5.
Finally, a correlation of story drift and damage states should be considered. This correlation would allow simpler analysis to find correct damage states without going through the complex analysis process. This can be done in multiple ways, with one being running multiple time-history analysis, logging average story drift, maximum story drift and the damage state. Assuming there is no significant torsion, the maximum story drift will be similar. A simple statistical analysis can find a correlation between story drift and structural damage state, allowing future simpler analysis for the same typology of buildings.

7- CONCLUSION

Pre-code large panel buildings in seismic areas present a challenge in estimation of seismic behavior. Part of the process in estimating seismic behavior is estimation of damage suffered after ground motion. In the case of large panel buildings, estimating damage of the building numerical model is complicated by the relatively complex behavior of its structural elements. This paper presents a procedure for estimating damage state of a large panel building, developed on a case study building, aligned with EMS-98 damage states.

A case study large panel precast concrete building is selected for analysis of seismic behavior through numerical modelling. The building is modelled through a combination of high fidelity and low fidelity models, allowing a simulation of the whole structure in a time-history analysis, with individual recast wall panels modelled. The relevant failure mechanisms of shear sliding, rocking and shear-key failure are considered at the level of individual precast panels. Each failure mechanism has its own limit states defined as limit of displacement and calibrated through a independent calibration process, providing each precast panel with 3 limit states (Limited damage LD, Significant damage SD and Near collapse NC) for each failure mechanism (shear sliding SH, shear key failure KEY, uplift AXt and toe crushing AXc). After each ground motion, damage state of the structure needs to be estimated based on existing limit states of precast wall panels. The damage states definitions are based on EMS-98 criteria with the aim to Damage state estimation is done through 2 separate processes, with one process considering all damage states, with no consideration for possible local collapse mechanisms, and the second process considering only local collapse mechanisms and consequently only considering damage states DS4 and DS5. The use of this approach to estimate global damage state, damage distribution and critical elements is discussed.

It is demonstrated that it is possible and relatively practical to estimate damage of a simulated large panel structure based on EMS-98 criteria. The approach demonstrated ability to estimate the damage state of any part of the structure, allowing global damage state estimation, identification of critical elements and damage distribution and finally ability to find correlation between damage states and story drifts. The approach demonstrated was able to conduct damage estimation on a numerical model with non-typical element layout, consisting of structured link elements simulating precast wall panels, rather than the usual walls, columns or other standard structural elements. Local collapse mechanisms are also considered through a simplified approach, ensuring adequate damage state assignment.

Among important limitations, the approach used to estimate element limit states is important to mention, as it is based only on maximum displacement. Each link in the model has its displacement linked to limit states by fixed displacement values. In experiments these displacements do vary based on axial loading of the precast wall panel, and importantly, cyclic nature of loading is not considered. In this model, expert judgment is used to obtain adequate behavior of the model, however further research can provide a better understanding of the rocking behavior of precast panels, especially under cyclic loading. This work provides a framework for future estimates of seismic behavior of large panel buildings, with various buildings having different precast panel geometry leading to different seismic behavior. Future research would include completion of the seismic analysis through incorporation of damage state estimation process into development of vulnerability and fragility curves, with the goal of better understanding of seismic risk for residents of pre-code large panel buildings.

8- ACKNOWLEDGMENT

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