EARTHQUAKE HAZARD CENTRE
NEWSLETTER

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Contents

Editorial: Soft Storeys

This newsletter is rather unusual in that it contains only one article. The topic is on soft or weak storeys and so a focus on this subject is totally appropriate given the huge problem they present. Soft storeys are the most common cause of damage and collapse of multi-storey buildings. It is probably not an exaggeration to say that most moment frame buildings in the world, as compared to shear or structural walled buildings, can be classified as soft or weak storey buildings.

In her paper, Teresa Guevara-Perez makes the point that not only are soft storeys the result of architects being attracted to some of the principles of the Modern Movement, but town planning regulations actively encourage their continuation. Her message is that we designers need to ensure that such regulations are amended so as reduce the likelihood of soft storeys occurring in new buildings. We all need to reflect on the regulations of our own countries to see the extent to which urban planning rules push architects towards designing such a dangerous structural configuration. If this unfortunate situation exists in our country, then Teresa would surely want us to dialogue with town and city planners to have the offending regulations changed.

In the paper, soft and weak storeys are explained. But, unfortunately, the problem is more widespread than that. It's clear that a building with ground floor columns higher than those of the storeys above will have a soft or weak storey. But, weak storeys are far more common than that. They occur in frame buildings where beams are stronger than the columns. That is almost every building! Unless during its structural design a moment frame has been designed according to the Capacity Design approach, then column damage leading to a weak storey is inevitable. Application of Capacity Design principles, that are embedded in more and more modern design codes, require columns to be stronger than the beams. It's far preferable for the ends of beams to suffer damage in the form of plastic hinges that columns to be damaged. Columns are often damaged to the extent of no longer being able to carry the weight of the building above – leading to collapse.

So, let's not under-estimate the soft/weak storey problem. We have to convince our urban planning colleagues to address it, and we have to avoid it at the conceptual stages of design.

Virtual Site Visit No. 37: Seismic separation of masonry walls

A two storey retail building is under construction in the city of Whanganui, New Zealand, located in an area of medium seismicity. The building consists of two storeys. The ground floor structure is a two-way reinforced concrete moment frame supporting a one-way precast flooring system (Fig. 1). Long-span steel portal frames support the first floor cladding and roof. They are pin-jointed above the first floor slab at their bases.

Since seismic resistance at ground floor is provided by the moment frames (columns rigidly connected to beams) in both directions, any reinforced concrete masonry walls need to be seismically separated from the frames. During an earthquake the frames will deflect horizontally several tens of millimetres. If separation is not undertaken, any walls which are far stiffer than the frames, would resist the horizontal movement and be severely damaged, possibly even collapsing.

Figure 2 shows two partition walls, one under construction. Vertical separation gaps at each end of the partially-built wall are visible. With these gaps the frame can move towards the wall without hitting it. Note that the walls are not connected to the concrete structure above except by small welded steel plates. These plates allow the floor structure to move freely above the wall in the direction of its length, but they support the wall against face-loads, preventing collapse.

The steel plates are seen more clearly in Figure 3. The horizontal separation gap between the top of the wall and the concrete beam above will be filled with soft material, like fire-resistant sealant. Note the steel beam half-way up the wall. This will support stairs and the stair landing. Since it is bolted with four bolts to the right-hand column, it is essential that any bolts into the wall it runs along must pass through elongated holes. Relative movement between column and wall must not be prevented. If elongated holes are not used, then any sway of the column will shear off the bolts and the stairs will collapse.

Engineers and architects need to pay close attention to separating stiff and strong non-structural elements like masonry walls.

Fig. 1 The ground floor reinforced concrete structure consisting of two-way moment frames supporting precast concrete flooring.

Fig. 2 A non-structural reinforced concrete masonry wall under construction. Vertical seismic separation joints are provided at each end of the wall.

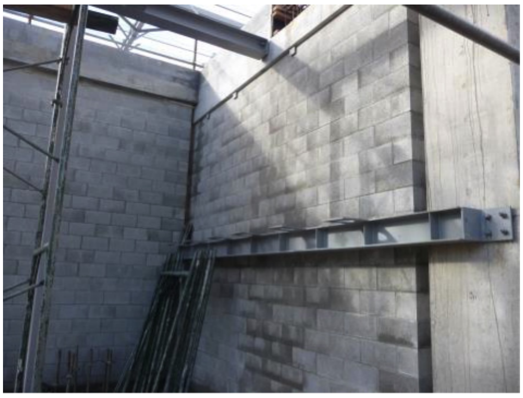

Fig. 3 The wall is separated from the adjacent column. The connection between the steel beam and the wall at the left-hand end of the beam needs to allow for relative movement between column and wall.

A Summary of "Soft Story" and "Weak Story" in Earthquake Resistant Design: A Multidisciplinary Approach" by L. Teresa Guevara-Perez. From the Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon 2012.

1. INTRODUCTION

In earthquake resistant design, the soft story and the weak story irregularities refer to the significant difference between the stiffness and the resistance of one of the floors of a building and the rest of them. Both configurations are known in architectural terms as: the open floor. The number of advantages given by this concept of modern architectural design, both aesthetical as functional, is the reason why it has been encouraged all around the world since the first half of the 20th Century. These conditions are present, when either the first story of a frame structure, known in some countries as "ground floor", is free of walls, while stiff non-structural walls are present in the upper ones, or when shear walls are located in the upper stories and they do not follow down to the foundations. The origin of this architectural configuration commonly used in modern cities is mainly derived from the three first points of the "Five points for a new architecture" published by Swiss-French architect Le Corbusier (LC) in 1926, that defines the tenets of modern architecture: (1) *pilotis* (open first floor); (2) the *free plan*; (3) the *free façade*; (4) *strip windows*; and (5) *roof terraces-roof gardens*. These postulates were possible due to the development since the 19th Century of new construction techniques and building materials, such as the innovative "reinforced concrete frame structure"(RCFS). The load-bearing structure consisted of solid slabs that transfer the gravity loads to the columns and finally to the footings, leaving behind the brick, mortar, stone and wood structural wall system that prevailed until early 20th Century. In 1914 LC developed the Domino System in France for economic housing, characterized by: elemental RCFS, which consisted of slender columns or pilotis, and flat solid slab (cast in place or precast) that covered long spans between columns, without girders. The RC solid slabs transferred the gravity loads to the columns, and then, finally to the footings. This new structural system also allowed the use of a floor layout free of walls. Since interior partitions did not receive any load, this structural system gave the freedom for modifying the location of them.

Most urban zoning regulations (UZR), consciously or unconsciously, encourage the use of the open floor configuration, since, when the first story is free of walls then the owner is rewarded. If this condition is present in the building, it is neither computable as part of the maximum allowable built area, nor for tax control, however, it is computable for selling purposes. But in seismic zones, from the beginning of the 20th Century this building configuration has been attributed as one important factor to the generation of seismic vulnerability in modern buildings. In reconnaissance reports, usually published shortly after each earthquake strikes contemporary cities all around the world, that evaluate the damage produced by earthquakes, the presence of it in damaged buildings is commonly mentioned, and it is also mentioned that it is closely linked to architectural decisions. These decisions usually are taken, either from the initial steps of the design process, or as consequence of subsequent remodeling.

2. SOFT OR FLEXIBLE STORY

The soft story irregularity, refers to the existence of a building floor that presents a significantly lower stiffness than the others, hence it is also called: flexible story. It is commonly generated unconsciously due to the elimination or reduction in number of rigid non-structural walls in one of the floors of a building. Table 12.3-2 in the *ASCE/SEI 7-10 document* defines soft story as irregularity type 1. If the soft story effect is not foreseen in the structural

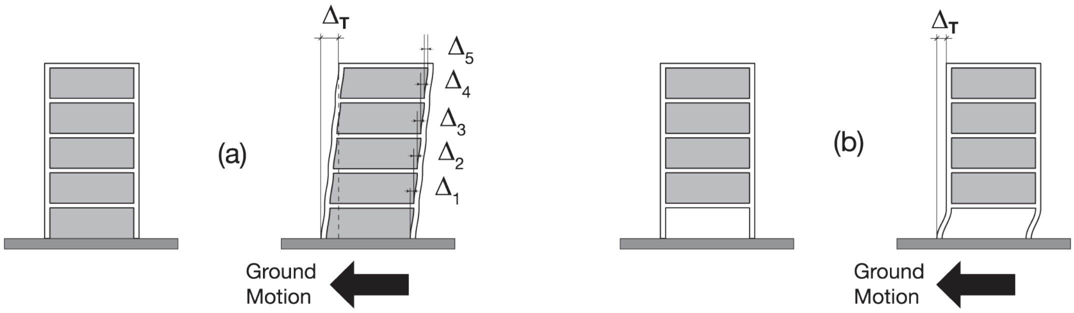

Fig. 4: Distribution of total displacement generated by an earthquake in: (a) a regular building; and (b) an building with soft story irregularity.

design, irreversible damage will generally be present on both the structural and nonstructural components of that floor. This may cause the local collapse, and in some cases even the total collapse of the building.

The *soft first story,* or *soft ground floor*, is the most common feature of soft story irregularity. It usually is present in modern frame buildings when a large number of nonstructural rigid components, such as masonry walls, are attached to the columns of the upper floors of a reinforced concrete frame structure while the first story is left empty of walls or with a reduced number of walls in comparison to the upper floors. The rigid nonstructural components limit the ability of the columns to deform, modifying the structural performance of the building to horizontal forces. In a regular building, the earthquake shear forces increase towards the first story. When a more flexible portion of the lower part of the building supports a rigid and more massive portion, the bulk of the energy will be absorbed by the lower significantly more flexible story while the small remainder of energy will be distributed amongst the upper more rigid stories, producing on the most flexible floor, larger relative displacement between the lower and the upper slab of the soft story (interstory drift) and therefore, the columns of this floor will be subjected to large deformations. See Figure 4.

The lowest more flexible portion at first story may create a critical situation during an earthquake. The stiffness discontinuity between the first and the second stories might cause significant structural damage, or even the total collapse of the building. One of the most common examples of soft story can be observed on the so called "*Open floor*" in the first story of modern residential buildings. The structural elements are homogeneously distributed throughout the building, but the apartments are located on the upper floors with many masonry walls. The lowest floor is left totally or partially free of partitions for parking vehicles and for social areas that require wide spaces. In the case of *double height first soft stories*, columns are very flexible not only due to the total or partial absence of walls but as a result of their significantly greater height in relation to those from the upper floors. This configuration is one of the characteristic models of modern design for office buildings, hotels and hospitals, in which the access for general public has a great importance. This configuration is also very common in mixed-use buildings, in which the urban code requires that the lower floors are of a greater height in order to accommodate shops with mezzanines for storage. As a variant of this configuration, we can find the use of columns of different heights in a corner of the building in order to give more importance to that space. Figure 5 shows two examples of modern buildings with double height first soft story configuration. In most of the earthquakes that occur in contemporary cities, there are always cases of collapsed soft first stories. Figure 6 presents two examples of recent severe damage due to soft first story irregularity in L'Aquila earthquake, Italy in 2009, and in the residential complex "San Fernando" of low cost housing in Lorca,

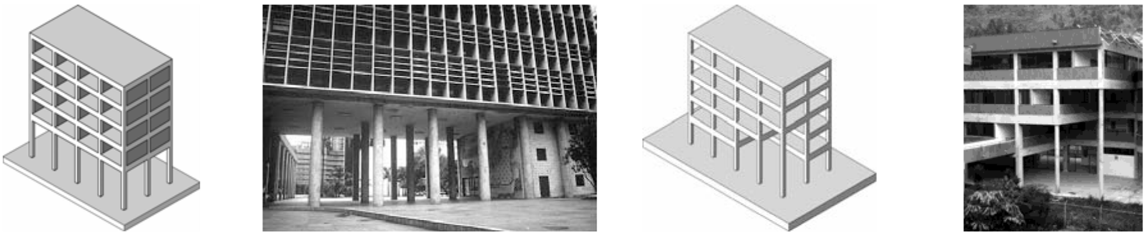

Fig. 5: Modern building configuration with double height soft story, the main entrance of the Ministry of Education, Rio de Janeiro (Photo: Jose Luis Colmenares); and partial soft story with columns of different height in the corner of the building (Foto: Klaudia Laffaille).

Fig. 6: Two recent examples of severe damage attributed to the soft first story irregularity in L'Aquila earthquake, Italy in 2009, (Photos, left: Holly Razzano, Degenkolb) and in Lorca, Spain in 2011.

Spain in 2011. The buildings didn't show apparent severe damage, though all the buildings of this complex that had a soft first story collapsed. The *covered sidewalk*, or arcade, is a configuration derived from soft story irregularity. It is a portico, like a cloister, in the first story of the front façade that is characteristic of buildings on commercial avenues. It is a common variation of irregularity in the distribution of the resistance, stiffness and mass of buildings, which is also included in UZR of contemporary cities as a heritage reference of the medieval city.

Another version of the covered sidewalks is the double height type. Most of the UZR include this configuration in mixed use buildings (commercial and residential), which allows double height first stories, a mezzanine for storage and double height showcase facing the covered sidewalk, in order to show the merchandise. The use in this case of very slender columns, as well as the use of double height empty spaces, creates an irregular distribution of the reactive mass, resistance and stiffness.

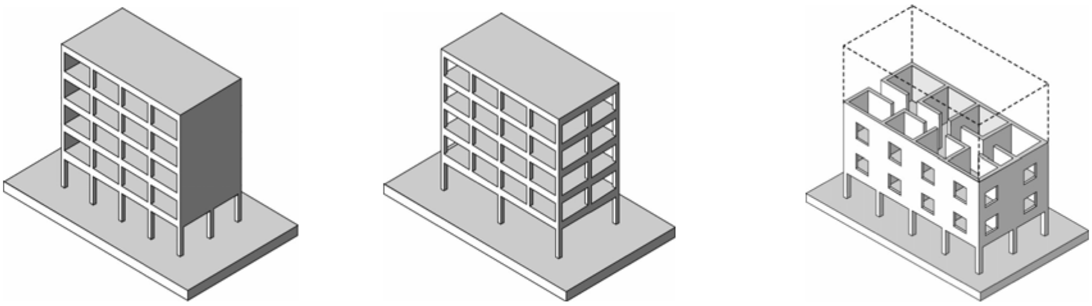

Fig. 7: Examples of weak first story irregularity.

3. WEAK STORY

This irregularity refers to the existence of a building floor presenting a lower lateral structural resistance than the floor above or the rest of the floors of the building. The building's weakest part suffers severe damage due to its inability to withstand the different types of loads produced by the ground motion. As an example, Table 12.3-2: *Vertical Structural Irregularities in the ASCE/SEI 7-10 document* illustrates this irregularity.

Weak story configuration is often generated in hotel and hospital buildings, in which not only the first floor has less walls than the other floors, but generally, due to its importance, it also has a greater height. A weak story can be generated by: (1) elimination or weakening of seismic resistant components at the first floor; (2) mixed systems: frames and structural walls, with wall interruption at the second floor or at intermediate floors. See Figure 7. This irregularity can also be present at the first floor or at intermediate floors. There are numerous examples of many buildings presenting a combination of these types of irregularities, soft and weak story, making them particularly seismically vulnerable.

4. AN EXAMPLE OF A DAMAGED BUILDING

The main building of the Sylmar Olive View hospital in the 1971 San Fernando, California earthquake consisted of four blocks joined around a courtyard, as shown at the structural layout in Figure 8. Each block had six floors and a penthouse. Bertero (1978) describes: "The structural system has significant discontinuities. While the upper four stories consisted of shear walls combined with moment-resisting space frames, the lower two stories had only a moment-resisting space frame system. The floor system consisted primarily of a flat slab-column system with drop panels at the columns. Tied and spirally reinforced concrete columns were used. The shape and reinforcement of these columns differed from story to story." The large interstory drift in the main Treatment and Care Unit, which induced significant non-structural and structural damage and which led to the demolition of the building, was a consequence of the formation of a soft story at the first story level because on the lower floors there were columns, while there were reinforced concrete walls above the second floor level. See Figure 8.

5. FINAL REMARKS

The open floor configuration is an architectural design feature that will not be easy to eliminate from architects' design criteria. It gives to the designer a series of functional and aesthetic advantages that are encouraged in schools of architecture and urban planning. But, it has

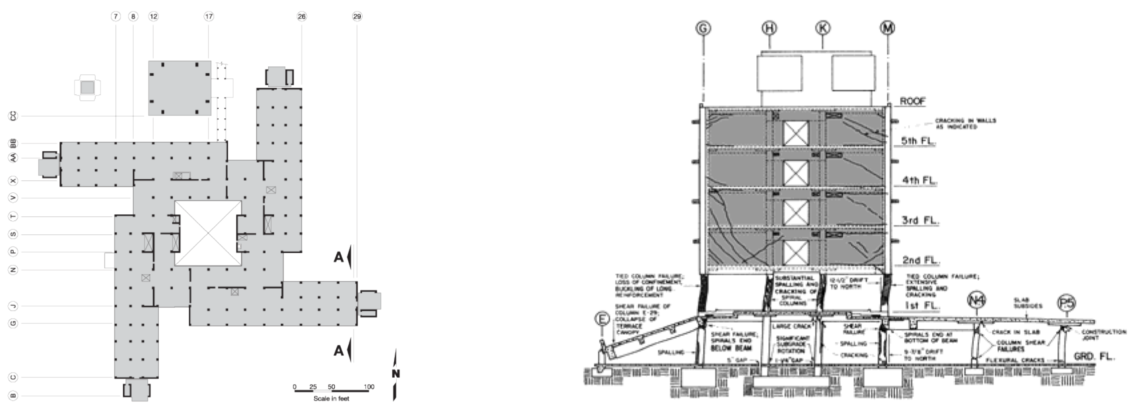

Fig. 8. First floor layout of the main buildings of the Olive View Hospital and Schematic Diagram (by L. Hashizume, E. Loh) of damage to frame 29.

been recognized by worldwide specialists in structural engineering, that this architectural configuration leads to the formation of soft and weak story irregularities. If not treated in a special way they produce severe structural damage and even the collapse of buildings when an earthquake occurs.

Arnold and Reitherman (1982) recommend:

> When shear walls form the main lateral resistant elements of the building, they may be required to carry very high loads. If these walls do not line up in plan from one floor to the next, the forces created by these loads cannot flow directly down through the walls from roof to foundation, and the consequent indirect load path can result in serious overstressing at the points of discontinuity. Often this discontinuous-shear-wall condition represents a special, but common, case of the weak first story problem. The programmatic requirements for an open first floor result in the elimination of the shear wall at that level, and its replacement by a frame. It must be emphasized that the discontinuous shear wall is a fundamental design contradiction: The purpose of a shear wall is to collect diaphragm loads at each floor and transmit them as directly and efficiently as possible to the foundation. To interrupt this load path is a fundamental error. To interrupt it at its base is a cardinal sin. Thus the discontinuous shear wall which stops at the second floor represents a "worst case" of the weak floor condition.

There exists a discrepancy between urban zoning regulations and seismic codes regarding vulnerable modern building configurations. Although since 1988 most seismic codes all around the world have included penalties for the use of these irregularities which results in the increase of the design lateral force or shear at the base, since the beginning of the 21st Century new categories were incorporated for controlling and even forbidding the use of these two types of configuration. Meanwhile, UZR of most contemporary cities in seismic areas all around the world continue to include incentives and in some cases the imposition of the use of the open floor architectural configurations without any limitation or structural restriction. They do not relate it to the soft and weak story irregularities that have been long recognized by earthquake engineering as seismically vulnerable. As an example of this practice, many paragraphs of the UZR of different modern cities promote the use of open floors at the first floor as a royalty to the constructor. The common practice of projecting buildings with this configuration, without any walls needed for delineating the parking, party halls or other communal spaces. This arrangement as a royalty to the builder, designer or developer, appears in almost every current UZR in contemporary cities. Also in mixed use buildings, shops and residences, located on major road corridors, the UZR usually obliges mixed use buildings to have a first floor for shops or public activities that is higher than the upper floors, often with no internal partitions. This allows the free distribution of shops and other spaces at the lower floor. Another configuration in UZR is the use of *covered sidewalks*, with a single or double height story.

Earthquake lessons have taught that is not sufficient to just apply structural engineering oriented building codes in the design of building. The problem has to be tackled with a holistic approach. Structural engineers, architects, urban planners, local authorities and the community need to participate, not only in reducing existing vulnerability, but avoiding the construction of future seismic risk. Interdisciplinary and transdisciplinary groups need to work together to establish urban policies and official instruments to avoid disaster due to seismically vulnerable buildings. Lessons also teach the necessity of having well-prepared and honest building inspectors.

6. RECOMMENDATIONS

If in contemporary cities in seismic zones the widespread use of the architectural configuration of open first floor is unavoidable, the recommendation is to include prescriptions in the UZR as well as the obligation to take measures to avoid at any cost soft and weak story

Fig. 9. Left: building in San Francisco (Photo: V. V. Bertero); right: former Alcoa Bldg. in San Francisco.

formation on the design of new buildings. Therefore, it is necessary either to prohibit them or to include prescriptions or restriction for designers in UZR, that allow them to reduce the vulnerability of buildings in those seismic hazardous zones. There are cities such as Alameda, Berkeley, Fremont and Oakland, California (http://enginious-structures.com/pages/softstory.html) that are already including in their UZR some restrictions and in some zones prohibit the use of them. At present, there are many analytical studies available on this regard in the structural engineering field, worldwide. Below, a summary of few solutions. When the "soft first story" irregularity is present it can be dealt with: (a) using strong and stiff complete elevator and staircase cores, which can take all the total base shear, leaving the first story columns almost only with axial loads; (b) by using diagonals to stiffen the first story; (c) by specifically designing the first story for much larger loads and smaller induced displacements than the rest of the structure, keeping the overall framed character of the building; (d) by making "transitions" where the "softness" is distributed in several stories (this is very delicate and needs careful tuning).

In 2010 Mayor Gavin Newsom of San Francisco proposed seismic mandates for retrofitting buildings with soft story buildings in the city. (See http://www.spur.org/book/export/html/1955 and ATC-52-3 Report in http://www.sfcapss.org/PDFs/CAPSS_522.pdf) Figure 9 illustrates some examples of methods that have been used in San Francisco for retrofitting buildings with first floor soft story. A multistory building that has been retrofitted by adding steel diagonal braces in two of the first story bays; and the recent retrofitting of former Alcoa Building are shown.

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Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

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