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Common Mistakes and Their Fixes in Earthquake-Resistant Buildings

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Abstract: The primary way to design building structures refers to the stationary loads specified by the governing laws. However, the load pattern does not guarantee the appropriateness of the seismic design. To make matters worse, old or ancient structures are traditionally reinforced for gravitational loads. This study reveals that the traditional reinforcement, in most cases, harms the seismic performance of buildings. The authors introduced the approach of most computer programs for seismic design, along with their limitations. Then, the ancient Roman approach was explained, and the reasons for the survival of many of these ancient structures were exposed thoroughly. After that, classical advices were summarized briefly for good seismic design of structures and reinforcement. Finally, a few classical mistakes were identified in reinforcement design.

Keywords: Earthquake; Building; Design; Reinforcement

1. Introduction

Although earthquakes have caused destruction since antiquity, it has only been during the last 50 years that contemporary knowledge of earthquakes and the impact they have on buildings has allowed for the development of earthquake-resistant structures. These structures are built with incredibly strong lateral bracing systems that can withstand the vertical and bending forces of earthquakes. In spite of this, there are still many earthquake casualties in the world. We believed we had witnessed the worst when the 1967 earthquake in Guatemala claimed the lives of 27,000 people. Yet, a subsequent earthquake north of Beijing killed 242,000 people.

Since the Earth's crust floats over a molten rock core, several parts of it tend to move in relation to one another. The relative motions exert stress on the crust, and may induce along fractures known as faults. Buildings nearby are shaken by the fracturing, and slide suddenly along the faults. The dynamic impact forces brought by the seismic motions can be handled by the same type of bracing that is used to guard against wind. The strength of an earthquake is often determined using the Richter scale, which gauges its energy. For instance, whereas an earthquake with a Richter scale measurement of 4 or 5 does little damage to well-built structures, an earthquake with a measurement of 8 or greater can cause structures to collapse and perhaps result in many fatalities.

Earthquakes can happen anywhere on the globe, despite that the worst ones happen in two sizable regions on the planet's surface. The western, northern, and eastern sides of the Pacific Ocean are traversed by the first region, while Asia Minor, the Himalayas, the East Indies, and the Mediterranean are traversed by the second. Devastating events known as earthquakes occur frequently close to the boundaries of tectonic plates, which are parts of the Earth's crust. When movement takes place in these places, along cracks, waves are created at the Earth's surface, and they can be quite damaging.

Smaller aftershocks always follow a major earthquake. They usually reach their peak in size and quantity within the first week following the first earthquake. They increase the danger of earthquake-related tragedies because they can dramatically reshake damaged structures. Aftershocks following moderate earthquakes (6+ magnitude) have frequently had sizes that were remarkably comparable to the first one. The frequency and power of aftershocks gradually decline. Typical patterns include at least one significant aftershock (within 1 Richter magnitude), at least ten minor aftershocks (within 2 Richter magnitude), 100 within 3 Richter magnitude, and so forth. The Loma Prieta earthquake was followed by a number of aftershocks, but the biggest was only magnitude

5.0 whereas the main quake's magnitude was 7.1.

The most harmful earthquake shaking impacts are those that create lateral loads in a structure. Building foundations fluctuate on a plane that is generally horizontal as a result of input shaking. Because of the building's inertia and tendency to remain in place, lateral forces pull it toward the foundation. For analysis purposes, this dynamic action is typically simplified in computer models to a set of horizontal forces that are applied to the structure in proportion to its mass and height above the ground. In multi-story buildings with equal-weight floors, the loading is further condensed as a collection of loads imposed at floor lines, each of which is greater than the one below it.

As they are built to withstand these lateral forces, seismically resistant structures need to be specified appropriately. These loads are typically stated as percentages and can represent anywhere from a few percent to almost fifty percent of the building's gravity weight. Only when concrete or bricks are utilized in a structure without the use of steel reinforcements do earthquake vertical loads overburden the vertical-load-resisting system. However, structures with a high dead load compared to the planned live load have been damaged by vertical forces brought on by earthquakes. These vertical forces also raise the risk of collapse because they either increase or decrease the compression forces in the columns. Columns are overloaded by increased compression and new tensile loads, while their bending strength is reduced by decreasing compression.

In earthquake engineering, we need to deal with random variables. Thus, the design process must be distinct from traditional design. From the traditional perspective, failure prevention is the major objective of design, as it makes variables appear deterministic. This simple approach is still helpful for design with only a little uncertainty. Contrarily, the impacts of earthquakes seem to render this common viewpoint useless. When dealing with earthquakes, there are considerable odds of failure. Structures now have modern devices that can capture significant vibrations and offer data on the response of the structure.

In this case, the upper floors exhibit a distinct amplification of both short- and long-period motions. Most seismic design codes incorporate this effect by applying stronger weights further up the building height. The practical assumption that a significant earthquake could occur at any time must be made by the building designer. The 1346 earthquake sequence at Ferrara, Italy, and the 1898 Charleston, USA, earthquake, are thus prevented from happening again by this approach.

The acceleration of a building depends on its period: short-period buildings typically experience more accelerations than long-period buildings. This phenomenon is considered in the acceleration values provided by the US-Geological-Survey (USGS) maps for short periods of 0.2 s and long periods of 1.0 s. These values, known as spectral accelerations, are similar to what a building experiences (in contrast to the peak acceleration at the ground).

The spectral acceleration is typically substantially greater than the peak ground accelerations. The USGS maps are based on the Maximum Considered Earthquake (MCE) ground motion. The USGS probability maps form the basis for the maps in building regulations that give the design values for spectral acceleration, which structural engineers use to determine the seismic forces acting on a structure. These design value maps are unique due to the usage of an MCE for the areas. However, in high-seismicity regions like coastal California, large-magnitude events that happen on a small number of clearly defined fault systems often manage the seismic hazard.

Instead of utilizing the 2% in 50-year likelihood, it is believed to be more acceptable to directly calculate the MCE ground motions based on the separate earthquakes of those identified faults in these regions. The acceleration values of the maps are not directly employed in design, it should be highlighted. Rather, engineers compute the Design Earthquake (DE) [1-4] using values that are lowered by two-thirds of this value. This is because engineers assume that the design codes incorporate a minimum 1.5-point safety margin against structural failure. This notion stems from the research on the earthquake resistance of various building styles, primarily in California.

The building reacts to an earthquake shaking within a short period of time. At this time, a variety of seismic wave types are merging to shake the structure in ways that are particular to each earthquake. In addition, the resulting shaking differs from place to place, because of changes in fault slippage, variances in the rock that the waves pass through, and variations in the local geology. Each structure is different in terms of its size, configuration, material, structural system, age, and level of construction quality; each of these factors influences how the building responds.

Albeit the complexity of the interactions between the building and the earth during the brief shaking, there is a general understanding of how different building types will behave under varied shaking conditions. The primary source of this knowledge is the vast global building earthquake observations, with some support coming from analytical and experimental research. To help architects perceive how their building will react to shaking and to guide their conceptual design, it is crucial to understand the ground and building characteristics.

2. Fundamentals of Seismic Codes

The contemporary focus on force rather than displacement in seismic design is largely a result of our growing understanding of structural dynamics and, more specifically, of the global improvement of seismic codes.

Although design techniques have been applied with increased strictness since the early 1900s, this fundamental force-based approach has not changed substantially. Because of this, seismic codes frequently classify seismic effects as lateral inertia forces. The height-wise distribution of these static forces appears to be implicit in the elastic vibration modes, indicating stiffness and strength.

Recent design codes like FEMA 356 and SEAOC Vision 2000 provide upper limits on response parameter values, which implies that any values higher than these upper limits contradict a performance target. The original distribution pattern of structural attributes may be changed through additional adjustments to the initial design with the intention of achieving performance objectives. Because structures surpass their elastic limits during powerful earthquakes, the distribution of structural attributes may not be ideal when inertia forces corresponding to elastic modes are applied. Numerous experiments and analyses have been conducted to determine the accuracy of the seismic code distribution of lateral forces.

It was shown in 2001 that there are differences between the shear forces caused by an earthquake and the assumed distribution pattern-based forces in a collection of 2–20 story frame models that had been subjected to various earthquake excitations. Researchers have studied how utilizing code patterns affects earthquake performance during the previous ten years. Several shear-building models were examined for how the El-Centro earthquake of 1940 changed them. The story-yield-strength of these models was chosen based on the distribution patterns of seismic forces specified by the Uniform Building Code (UBC). The first story typically has the largest flexibility demand of all the stories as a result of this distribution pattern, which does not lead to equal flexibility demand across all of the stories.

A variety of arbitrarily chosen distribution patterns, as well as the UBC 1997 distribution pattern, were used to proportion a number of shear building models. It has been found that different patterns can create a uniform distribution of flexibility with a lower maximum flexibility demand. The code's pattern does not produce a uniform distribution of flexibility. These results have been supported by additional study, which has produced a novel concept known as the "optimal distribution pattern for seismic performance." It is often attempted to produce homogeneous distortion across the structure in order to get the optimal design.

Several researchers observed that the weight of a seismic resistant system necessary to achieve the specified flexibility and the coefficient of variation (COV) of the story-flexibility-demands are associated for a specific earthquake and diminish simultaneously. They came to the conclusion that it is possible to determine whether design load patterns make the best use of material by using the COV of flexibilities. The effectiveness of typical loading patterns in obtaining equal flexibility demands across all stories is examined by subjecting shear-building models with a range of periods and flexibility needs to 20 chosen ground motions.

Strength and stiffness are distributed throughout the stories in each case in accordance with the lateral load pattern proposed by UBC 1997/EN 1998-1-2004. The required fundamental period is then modified by scaling the stiffness pattern after that. Next, a non-linear dynamic analysis is done to determine the maximum flexibility demand for the specified step. The maximum flexibility demand is increased iteratively until it reaches the target level with less than 1% inaccuracy, at which point the model's overall strength is increased without changing its distribution pattern. The COV of the story flexibility demand for each situation are then determined. When the UBC 1997/EN 1998-1-2004 strength pattern is applied, the flexibility requirements for the buildings falling within the linear behavior range are distributed almost uniformly.

Conventional load patterns are less effective in nonlinear vibration. It has been proven that increasing the target flexibility always coincides with increasing the COV of story flexibility demands. In systems with an extremely long fundamental period and an incredibly short fundamental period, the COV of story flexibility needs are exceptionally high. Every structure contains fundamental natural modes and frequencies, known as naturals, which determine the pace at which they will oscillate if pressed horizontally. Another crucial factor in seismic design is the frequency distribution and wave amplitude.

A seismic push that starts a building moving must be as near to its natural period as feasible in order for it to be significant (resonance). The natural period of a filing cabinet is roughly 0.05 s, while that of a one-story building is about 0.1 s. The cabinet will vibrate at a rate of 20 cycles per second, or Hz, or a period equal to 1 divided by 0.05. According to a general formula for preliminary design, taller buildings between 10 and 20 stories will sway at times of roughly 1 to 2 s. The building period is equal to the number of stories divided by 10. As a result, period is mostly influenced by building height.

The 60-story Citicorp office building in New York has a measured period of 7 seconds. Height is the most crucial factor, although the structural system, materials used in construction, content, and geometric proportions all affect the period. A building's period can also be changed by earthquake damage, lengthening the structure's vibrational period because this building is getting softer. This could result in resonance and give the structure a period similar to that of the ground, which could be catastrophic to a weak structure. For many years, seismic building codes have been solely concerned with the system of columns, beams, walls, and diaphragms that offers resistance to an earthquake's effects.

For obvious reasons, this continues to be the main focus, but recent earthquakes have revealed that damage to non-structural components is also a serious concern. Most modern buildings' nonstructural components account for 60% to 80% of their worth. The bulk of nonstructural components are weak, simple to break, and expensive to replace or repair as compared to the building's structure. Differentiating between structural and nonstructural system components and the system as a whole is frequently artificial. All parts that were not meant to be a part of the seismic Lateral-Force-Resisting system (LFRS) are classified by the engineer as nonstructural.

Nature, on the other hand, examines the whole structure and does not distinguish between them. Many nonstructural components could be necessary to resist forces even though that is not what they are designed to do. Nonstructural systems or components have the potential to change the structural response in ways that endanger the building's safety. Two instances include the formation of a short-column condition due to the placement of nonstructural partitions between columns and the installation of heavy nonstructural partitions in locations that result in significant twisting and stress concentration. This could lead to column failure, deformation, and extra nonstructural damage. The building is at danger for electrical or gas system fires following the earthquake, for the sprinkler system may have failed due to damage.

Although being far from the epicenter will typically mitigate the impacts of the earthquake on the building and its nonstructural components, safety is not always ensured by distance (San Francisco was roughly 60 miles from the epicenter). Nonstructural failures are typically visible from farther away than structural failures. The vertical component of earthquake shaking was hardly considered by model earthquake codes in the past. The ratio of the maximum horizontal ground motion to the maximum vertical ground motion is normally between 60% and 70%.

It is frequently not required to take the structure's overall vertical motions into account in nonstructural design. The model codes hardly ever specify the vertical acceleration design criteria for nonstructural components. The building pattern often amplifies both horizontal and vertical motions. Even though the code normally does not mandate vertical design resistance, the designer must be cognizant of the implications of vertical vibrations during an earthquake and their potential effects. It has been plainly obvious for a long time that regular and prismatic structures, with their nonstructural elements and seismic design, are both easy to conceptualize and construct.

However, the present tendency in architectural design toward complicated shapes has led to a rise in the complexity of nonstructural systems. As complexity increases, we become less able to anticipate how systems and components will behave and interact. Nonstructural components, however, may also have an impact on the structural reaction to ground shaking. In structural analysis, the bare structure is presumptive. Depending on their location, heavy contents and nonstructural components linked to the building may create a torsion force. The following are typical examples of interactions between structures and non-structures:

Rigidly bonded heavy masonry partitions that are precisely positioned next to floor slabs and columns can provide a localized stiffness that causes stress concentrations and torsional forces. This particular condition has caused considerable structural damage when partial brick walls are installed between columns to produce short-column conditions. The construction of such partial walls after the structure is finished is typically seen as a modest refurbishment, which does not seem to require engineering analysis. The shorter column's high relative stiffness draws a considerable amount of the earthquake forces, frequently resulting in collapses. In smaller buildings, stairs that serve as bracing members between floors can create strain. The answer is to separate the stair from the floor slab at one end to permit free structural movement.

3. Roman Aseismic Structures

The Roman Republican and Imperial eras saw a sizable number of advancements in building methods and structural design. Some of these developments, most notably the creation of Roman concrete, naturally improved the seismic capabilities of the buildings. The field of applied science known as seismic design barely emerged in the 20th century. Despite this, many of the fundamental building blocks that can provide earthquake protection have been included into Roman-era constructions.

The Roman State structure was distinguished by its capacity for organization and rule, both throughout republican and imperial periods. The Roman government kept a sizable army that could be utilized for public works projects, and it also had access to a substantial number of captured slaves who could be used as labor. Large structural components had to be extracted and chopped during pre-Roman construction techniques like the Greek ones. This could only be done by Masons and experienced craftsmen.

The Romans created a distinctive building method thanks to their army of laborers. Large quantities of valuable building materials were assembled under the direction of a few experts and an engineer, and construction moved forward as a series of repetitive tasks carried out by the enormous workforce. A new type of monolithic concrete construction emerged as a result of this fundamental shift in construction approach. Roman monolithic concrete structures are incredibly robust, unlike earlier Greek ones built of stone blocks joined together with ductile linkages. The foundations were designed taking into account the corresponding stiffnesses of these structural forms.

In Greek architecture, the foundations stood apart from the building's supporting elements. Uneven settlements or relative ground movements have little impact on the structure's elements, because superstructures consisting of massive elements have a yielding nature. The extraordinarily inflexible enormous foundation mats that supported the robust Roman structures shielded the superstructure from the impacts of the relative soil displacements.

Compared to most other structural design elements, foundation design has been studied and understood to a much greater level than most others. This is evident from Vitruvius' emphasis on foundations in De Architectura (e.g.: I 5, III 4, V 3 and VI 8). Roman concrete is hand poured in horizontal courses, with mortar and stone aggregate layers alternated. The light masonry beams that would subsequently make up the final walls' façade were sandwiched between the concrete blocks. Bricks, primarily, and bastard mortar are used to construct the beams. The resulting structures act obviously as a monolithic mass, while appearing to be constructed of lightweight masonry. The holes for the scaffolding, as well as the concrete "glue paths" and relief arches, are visible. Given that Roman structures were almost always covered in plaster or a similar wall covering, it is obvious that these elements were functional rather than decorative. On concrete "sticking paths," which serve as crack-stoppers, earthquake cracks come to a stop.

The degree of structural integrity that could be obtained significantly increased with the following development of the monolithic concrete structure. Previously given by "support" and friction, structural integrity is now improved by the cohesion and homogeneity built into the mass of concrete. Understanding Roman monolithic constructions requires two key components: "cement crack stoppers or glue paths," which enable bearing masonry to travel on favoured, pre-defined surfaces when lateral seismic loads arise. Large amounts of energy are absorbed by the structure during movement, and the primary stresses are released from the supporting structures.

Brick relieving arches are built inside very large bearing walls and are known as relieving arches. These arches were required to provide a reliable method of transporting the weight of the concrete while it was setting. Regarding labor and energy costs, Roma cement was a very expensive material. Therefore, Romans used bastard mortar and cement. Bastard mortar was common for brick and masonry structures up to the 20th century. Roman cements and Bastard mortars both required extensive curing times. The masonry was not supporting much weight during this prolonged period, which may have lasted several days depending on the weather. In order to offer the walls bearing capacity before cement and bastard mortar hardened, arcs were inserted inside the walls. The element that causes the hardening, water, was periodically sprayed on the walls during the process. Hence, cement was applied only a few selected areas of the building, i.e., the “crack stoppers”. Brick courses that are aligned at the corners strengthen the structure's stability and increase its capacity to respond to horizontal seismic loads with a combined action of all the wall systems.

Probably the most significant architectural innovation of the Roman Architectural Revolution is the monolithic dome (58 - 138 AD approximately). Concrete domes were built pn false works supported by timber frames. The "ribbed" domes were constructed using vertical courses of tiles, either in the shape of relief arches or ribs that ran from the apex to the base. These were believed to support the dome's structure, much like the "glue paths" of the walls. The inclusion of the ribs was more likely done to reduce the effects of shrinkage or to compartmentalize the concrete mass, making it easier to lay and compact. Ribs were either used or left out of domes of various sizes; there did not seem to be a rule of thumb to include them. The "ribbed" domes frequently have pillars in the dome's drum as well. This type of building, which features pilasters and noticeable arches or ribs, may have evolved from framed structures to the monolithic casings of later domes.

The traditional shape of Roman domes is spherical, which reduces the thrust forces at the top of their drums. Roman domes frequently curve upward as support requirements diminish to further lessen these stresses. Also, the classification of aggregates is applied in some domed buildings, with lighter materials utilized closer to the apex. Lower thrust forces are produced by the combination of aggregate classification and shell taper. The Pantheon's dome shows no signs of earthquake-related damage. There were a few cracks found, pointing to the drum's torsional response close to the dome-drum interface. One must rely on data from a repair project from the 1930s because this damage is not readily apparent. The nature and characteristics of the cracks imply that they are a result of the great irregularity that the incorporation of the gigantic portico imposed into the building. The Pantheon is nevertheless a unique example of Roman aseismic construction, in addition to Roman architecture, despite this relatively slight damage [5, 6]. Roman aseismic design relied on crack specified paths and lightweight buildings in the upper parts. Large, sturdy foundations were additionally crucial.

4. Mistakes in Building Design

Configuration irregularity is largely to blame for the tension concentration under stress. Unfavorable force concentrations can be caused by stress that accumulates in irregularities, which in turn induces abrupt changes in stiffness or strength. When numerous building elements, such as a group of beams, columns, or walls, are the focus of significant stresses, this is known as stress concentration. These few members could fail, leading to damage or perhaps the building collapsing as a result of a domino effect. Stress concentrations may result from both vertical and horizontal stiffness differences. The short-column phenomenon is a stress concentration brought on by vertical dimensional irregularity in the building's design.

The plan arrangement that is most likely to bring stress concentrations is the reentrant corner condition, which is exemplified in buildings with plan forms like a L or a T. The soft- or weak-story vertical irregularity can lead to potentially dangerous stress conditions along the plane of discontinuity. The soft story is typically created by a first floor that is open and supported by thick structural or non-structural walls above. This issue gets even worse if the walls above are shear walls acting as important lateral force resisting structures. Slender columns and tall first floors, however, are not usually a sign of soft stories. In order to have a soft story, the flexible columns must be the primary lateral force-resistant mechanism. When shear walls are a structure's primary lateral-force resistance components and there is not a continuous load path from the roof to the foundation, discontinuous shear walls can cause substantial overstressing at the discontinuity points.

The discontinuous shear wall condition is a special yet common case of the soft-first-story problem. At each story, the shear wall efficiently and directly gathers and distributes diaphragm loads to the base. It is not a good idea to divert this load path. Interrupting it at its base, where the shear pressures are greatest, would be a grave error. As a result, the worst-case discontinuous shear wall at the second floor might serve as a representation of the soft-first-floor situation. The story in a building that must support all of the other stories should be sacrificed last rather than first because a concentration of loads is caused by a discontinuity in vertical stiffness and strength.

For the purposes of seismic design, structures with irregular configurations that are mathematically regular and symmetrical may experience variations in perimeter strength and stiffness. The perimeter design of the structure significantly affects the seismic behavior of the building. If there is a large range of strength and stiffness around the perimeter, the center of mass will not correspond with the center of resistance, and torsional forces will usually cause the building to rotate around the center of resistance. This issue can be resolved by lessening the possibility of twisting by leveling the resistance around the circumference.

Steel, concrete, and composite material systems can create a frame structure that is roughly equally strong and rigid all the way around. The opaque part of the perimeter can be built using nonstructural cladding that is intended to not impair the seismic performance of the frame. This can be achieved by separating heavy components like concrete or masonry from the frame or by employing lightweight cladding.

A second strategy would be to raise the stiffness of the open facades by adding enough shear walls at or close to the open face that are intended to approach the resistance offered by the other walls. A third strategy would be to use a sturdy moment-resisting or braced frame at the open front, which is stiffer than a solid wall. How well this works will depend on how big the facades are. On the other hand, a long concrete wall will always be more rigid than a long steel frame. The structure can be made to both resist torsion and accept the potential of it through the use of moment frames, braced frames, and shear walls. In most cases, when a structure is severely shaken, the beams will fail before the columns. As a result, there is a lower chance of complete collapse.

Similar to the accidently occurring weak-column, strong-beam scenario that happens when stiff or strong nonstructural elements are placed between columns. We often tolerate larger risks of damage when subjected to seismic design loads compared to other equivalent extreme loads, such as maximum live load or wind loads. This is because the seismic forces produced by strong ground vibrations are too enormous to resist within the elastic range of material reaction. Therefore, it is common practice to design for forces that are only a small portion of those associated with elastic response. We thus predict that the structures will endure strong earthquakes, owing to their significant inelastic deformations and energy dissipation properties [7-15].

Whilst an earthquake can inflict damage to a structure, the collapse is brought on by the weight of gravity. Critical members' ductile behavior as well as a redundant load channel can lessen or even prevent collapse. But brittle behavior makes collapse more likely and more severe. Due to a growing understanding that extreme strength is neither necessary nor even necessarily desirable, the focus in seismic design has switched from resistance to escape of strong seismic forces. Inelastic structural response has developed into a crucial reality in structure design for earthquake forces.

Inelastic deformations that offer flexibility are regarded to be crucial for averting building collapse when the structure is subjected to back-and-forth motions during strong ground shaking. Seismic design favors structures that are more likely to be ductile over those that are not. Therefore, for concrete buildings, a member's shear strength must be greater than its actual flexural strength. Spalling of the concrete and instability of the compression reinforcement will take place, if sufficient, precisely spaced, and well-detailed transverse reinforcement is not put in the probable plastic hinge zone.

A column plastic hinge can nevertheless form at the base of the column, leading to partial or complete collapse, even in a weak beam/strong column design, where well-confined beam plastic hinges are used to disperse seismic energy. It is not viable to simply extrapolate and apply tried-and-true techniques for designing structures for different static loads, including wind forces, to earthquake-related circumstances. We must constantly take into account the forces that correlate to the maximum seismic displacement while designing for earthquakes.

As repeatedly noted in earthquakes, interference with the deformations of members by inflexible nonstructural features like infill walls is a primary cause of damage, particularly in columns. The top edge of a brick wall will shorten one of the columns' effective lengths and stiffen its lateral members in the case of these short columns. Since seismic forces are inversely related to stiffness, the braced column will experience higher horizontal shear forces than it would otherwise. If these gravity load-carrying parts fail, the entire structure could collapse. Therefore, it is essential to ensure that nonstructural construction does not obstruct the deformations of the inelastic column.

Tall structures with poorly defined joints are more susceptible to earthquake damage or even failure. The structure's back-and-forth motion during strong ground shaking runs the risk of rupturing moment-resistant joints. The gravitational load can no longer be supported by these columns. The building is forced downward as a result, stopping on the ground or lower floors that can withstand the weight of the descending mass. Higher-up structures are often where tension/compression problems occur. When tension is focused at the edges of a concrete frame or shear wall, stability can be lost very quickly. If the reinforcing steel is improperly proportioned or not lodged in the wall, it can overturn and fail in tension, triggering a quick brick wall collapse. This is a very common problem, where tension results in the joints of a concrete moment frame losing their bending and shear strength. Broken joints in poorly specified joints might cause column failure.

As shown in Figure 1, the bell tower was exposed to brick wall flaws. A significant local increase in bending stiffness was introduced by the reinforcements made of horizontal steel strips and tie rods, acting as a notch during the earthquake. High local strains caused by the strips eventually led to the masonry's demise. This phenomenon can be understood by the basic equation of a cantilever beam free vibrations (1):

$$f = \frac{\alpha^2 \sqrt{\frac{EI}{l^4 m}}}{2\pi} \tag{1}$$

where, f is the natural frequency [Hz]; E is Young's modulus [Pa]; l is the tower height [m]; m is the linear mass [kg/m]; I is the area moment of inertia [m^4]; α is 1.875 for the first natural mode. The small E and I indicate that the bell tower has very low natural frequencies. The linear mass m is high due to the masonry mass. Therefore, the bell tower may easily resonate during an earthquake:

$$x \frac{m \rightleftarrows al^4}{8EI}_{max} \tag{2}$$

If the acceleration a of an earthquake is high [m/s^2], the tip would displace significantly (x_{max} [m]):

$$\beta \frac{mal^3}{6EI}_{max} \tag{3}$$

The tip will rotate by large angle β_{max} [rad]:

$$M_{mx} = \frac{mal^2}{2} \tag{4}$$

The maximum flexural moment M_{mx} [Nm] will be also significant. Therefore, the most significant load will be the bending stress. The tower surface will be under the most pressure. Due to steel's high stiffness in tensile stress compared to masonry and cement, the horizontal metal strip's presence on the tower surface will cause a geometrical discontinuity. The peak stress in the masonry will be greater than the uncertain and relatively low maximum tensile stress of the wall.

Figure 1. Steel strips enhancing seismic earthquake flexural stress on the bell tower (bad solution)

A more effective method of bell tower reinforcement is shown in Figure 2. The flexural loads are supported by the vertical beams, and a compressive force is generated and the brickwork is kept together by pretensioned transversal wires. A poor strategy for improving the seismic performance of a small building is shown in Figure 3 and Figure 4. The structure foundations are made of reinforced steel. Well-designed double courses of bricks support the vertical loads. The roof is made of hollow core reinforced concrete, while the flooring are steel-reinforced joists. The initial plan to strengthen the building involved adding tie rods to link up and stabilize the brick walls and lay down a reinforced concrete wall at ground level (Figure 3 and Figure 4).

These two reinforcements are quite efficient and will enhance the seismic performance of the building. Unfortunately, three additional metal strips were included. By adding variations in stiffness and a notch, they will lessen the resistance of the brick walls, much as the tower bell in Figure 1. Vertical steel strips should be also added to improve the brick wall resistance to horizontal loads.

Figure 2. Vertical steel reinforcements and compressing wires (good solution)

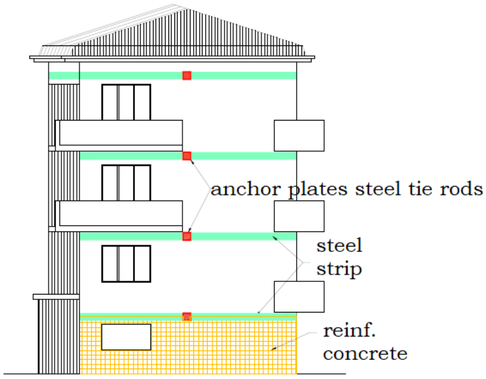

Figure 3. Reinforcements on a building (bad solution)

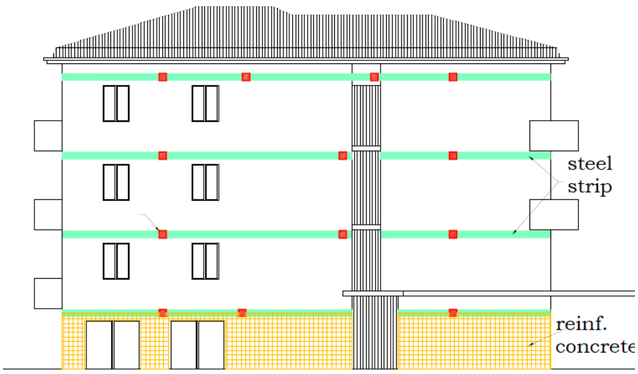

Figure 4. Reinforcements on a building (bad solution)

5. Conclusions

Seismic engineering is quite similar to other engineering disciplines. Effects of earthquakes on structures routinely reveal even the smallest flaws in design and construction. The design is made even more crucial by the extremely random nature of everything, the significance of soil–structure interaction, and the undeniable dynamic nature of disturbances. To gain valuable experience, structural engineers should be exposed to earthquake engineering concepts, even if their interest in earthquake-resistant design is indirect. They will gradually come to the realization that the challenges posed by seismic design are technically fascinating, and they will start employing the enigmatic ability known as engineering judgment to take into account these unknown factors.

Whatever the building's type, size, or purpose, it is abundantly evident that any attempt to promote or compel the usage of standard configurations would typically fail. The architect is highly successful in the search for historic shapes.

For instance, the seismic standards in ASCE 7-10 are focused on practical, cost–effective construction and take the low-key approach of imposing modest penalties on the use of irregular configurations in the form of increased design forces and, for larger buildings, more sophisticated analytical techniques. Both of these actions entail financial penalties, which the building owners may be willing to pay. Only two irregularities—extreme torsion and soft stories in vital buildings situated in high seismic zones—are expressly forbidden (i.e., buildings categorized as Seismic Design Category [SDC] E or F). This suggests a design that takes advantage of the ideal configuration while enabling the architect to use irregular forms when they serve the purposes of the design.

Extreme irregularities could necessitate extreme engineering solutions. Even though they could be pricey, a structure with these conditions is probably unique and important enough to justify the additional money needed for materials, finishes, and systems. Designers should never use a weak or soft story. This does not exclude the use of tall or a variety of story heights, but it does require that the proper structural precautions be taken to ensure balanced resistance. When evaluated through a seismic lens, it seems that many practical and ubiquitous architectural shapes are in conflict with seismic design requirements.

If they are to resolve these differences, the architect and engineer must work together on the building design from the start of the project and participate in skilful discussion. It is unfair to expect the engineer to convince the architect of some traditional earthquake design ideals like regularity, simplicity, and symmetry.

Building configuration discussions of this nature are only pertinent for projects where cost effectiveness is the primary objective. As desired by the architect and the client, high-style designs are likely to have uneven, asymmetrical, and fragmented forms. The successful engineer will love the difficulties. Engineers must continue to develop their own intuitive understanding of how structures work and the ability to see the complex interactions between building components that emerge from a variety of factors, both practical and aesthetically. While new analytical techniques will be useful, engineers must also keep cultivating their own intuitive sense.

Using the Roman approach, architects should design buildings with lower story mass as height increases. In this sense, a wooden roof without tiles is better than a reinforced concrete roof with tiles, and a roof of sandwich panels is even better. They might also add walls or light-weight bricks to the construction that could crumble and absorb energy. In a more modern approach, concrete that is not very effective in terms of max-stress to weight ratio can be reinforced with steel, glass fiber, and carbon fiber. This is crucial when talking of dynamic loads that may cause tensile stresses on vertical columns as well. The golden rule directs failure toward horizontal rather than vertical aspects. It is also crucial to have consistent stiffness or stiffness continuity. This paper elucidates several bad reinforcement approaches and explains how to fix their mistakes.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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