Sustainability of Earthquake Resilient Near Zero Energy Buildings

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The climate crisis, the need for a circular economy, and the large financial losses after earthquakes have promoted the concept of the sustainable and resilient design of societies, and more specifically, of lifelines and building environments. Focused on building facilities, it is imperative to prescribe, within the aforementioned framework, the components that characterize earthquake resilient near zero energy buildings (ERnZEBs). This fact introduces an additional factor recognizing that not all projects have the same technical and financial values; the difference in budget, the type of owner, and the investment (private or public, company or private person) play important roles in creating an ERnZE building.

Keywords: earthquake sustainability ; earthquake resilient near zero energy buildings (ERnZEBs)

1. Introduction

Starting from the principle of Vitruvius [1], that all buildings must have three characteristics, namely *Firmitas* (Strength), *Utilitas* (Utility), and *Venustas* (Beauty), and moving on to the current strong urbanization that needs sustainable and resilient societies against multiple hazards (earthquakes, floods, tsunamis, fires, and explosions) [2][3][4][5][6][7], it is of paramount importance to define the attributes and perspectives of the basic components of communities and societies, which include new and existing building facilities. Definitely, buildings are a sub-system as compared with the whole system, but they make a great contribution to the built environment.

Focused on earthquakes, major studies were performed and published that were associated with building resilience [8][9][10][11], providing framework methodologies and tools generally based on probability. To this end, one can mention that sellers like real estate developers, insurers, reinsurers, and bankers, as well as asset managers, think about and take decisions in a probabilistic way. This is due to the fact that probability is never unfair and shares responsibility and liability as well. Instead, buyers of buildings are characterized by a deterministic way of thinking. They want to buy an asset that will be durable and resistant for a long time, with minimum maintenance, and without structural damage, building downtime, or financial losses in its life cycle. This is true for someone who buys, although it is not true for technical and financial stakeholders. Therefore, there is a gap between them. The building's environment and seismic action are inherently variable and uncertain. Although it should be recognized that seismic risk is strongly influenced by political decisions, it is more specifically a tradeoff between risks and costs for a given known hazard. The question that arises is: how much does a typical homowner know about the acceptable risk? Moreover, what is the financial capacity of a typical homeowner to take a risk? Unbeknownst to the homeowners, this risk has been taken by the design code without their even knowing it.

Coming back to the Vitruvius attributes and translating them into the current construction practice, a building must be aesthetic, structurally durable against environmental actions, founded on stable soil with a structurally sufficient bearing capacity against static (i.e., dead and live actions) and dynamic loads (i.e., wind and seismic actions), water resistant, thermally and acoustically efficient, as well as fireproof. A building should not only be mechanically resistant from geotechnical and structural points of view; it is not sufficient. The aforementioned attributes define only an Earthquake-Resistant Energy Efficient Building.

Nowadays, this is not sufficient. The climate crisis, the need for a circular economy, and the large financial losses after earthquakes [12][13], promoted a twofold target: (i) a shift from fail-safe to safe-fail [3], or specifically, a design shift from collapse prevention and life safety to a resiliency towards full pre-earthquake functionality [14][15] and (ii) the development of buildings that are characterized by a very high-energy performance during operation and where most of the energy required is provided by energy from renewable sources (typically solar thermal and photovoltaic (PV) systems) [16] (or the new, very optimistic proposal of zero emission buildings [17]). With regard to the first target, beyond the stiffness, strength, and ductility, in addition, the adaptability and reparability capacities within a tolerable timeframe after an earthquake were considered. Related to the second target, buildings must have the necessary system supplies along with efficient insulating composite systems that limit the HVAC's (heating, ventilation, air conditioning) consumption.

According to the above-mentioned issues, such buildings could be described as Earthquake Resilient near Zero Energy Buildings, ERnZEBs. Consequently, this prototype building has the following attributes: the ability to be durable against environmental actions; to avoid foundation soil failure; to prevent collapse and to protect life safety; to develop, after an earthquake, repairable damage to structural and non-structural elements; to recover and restore its occupancy and functionality after an acceptable time (after an earthquake); to be allocated very high-performance systems, reducing energy consumption and CO_2 emissions; to be waterproof, fire resistant, and acoustically efficient. The first five characteristics are connected with geotechnical and structural design, while the remainders are associated with building physics. Certainly, architectural functional adaptability is a prerequisite for such buildings. ERnZEBs go beyond the current trend of seismic resilience and energy efficiency. Equally, it must be taken into account that there is a need for durability, water, and fire protection, as well as acoustic comfort. In any case, all the elements, connections, and systems that offer the benefit of near zero energy buildings must be earthquake resilient. Finally, ERnZEBs must have similar attributes for new and existing buildings, taking into account the construction period and the desired level of improvement. Overall, the two pivotal pillars of an ERnZEB are sustainability and resiliency; a strong interdependency between them is required.

2. Earthquake Sustainability of ERnZEBs

The climate crisis and the resulting environmental changes strongly promote sustainable development. According to the UN's Brundtland Commission [18], economic growth for a sustainable society must meet the needs of the present without compromising the ability of future generations to meet their own needs. However, as reported by the World Green Building Council [19], the building sector (production of building materials, transportation, construction, and demolition) is responsible for 39% of global carbon emissions. Focused on the consequences of strong earthquakes, and more advanced than severe damage, are the collapsed buildings and their demolition wastes, a serious problem that perturbs sustainability. Moreover, the collapsed buildings should be replaced with new ones. As an example, approximately 70% of the district of Christchurch, after the 2011 earthquake, was demolished (namely, over 60% of the reinforced concrete building with three stories and more, around 1000 commercial properties, and 10.000–15.000 residential properties) [20][21]. The recent Kahramanmaras earthquake in Turkey in 2023, which affected nearly 16 million people, resulted in approximately 280.000 buildings collapsing or being severely damaged; hence, it was the second most severe case of post-earthquake demolition [22]. All of the above-mentioned real facts violate the three basic principles of sustainability: *Reduce*, *Reuse*, and *Recycle*. It is, therefore, clearly stated that an ERnZEB must respect the rule of Rs. It should be valid for both new and existing building structures. However, it should not be forgotten that, in earthquake-prone countries, sustainability continues through the earthquake. This means that every energy and environmental design should be supported by a resilient structural design. Otherwise, there is a loss of investment; see **Figure 1**.

(a)

(b)

Figure 1. (**a**) L' Aquila earthquake, Italy, 2009, and (**b**) Kahramanmaras, Turkey, 2023. (Photos from European-Mediterranean Seismological Centre).

Evidently, sustainable construction is limited by the use of energy minimization, raw materials, gas emissions, and waste generation and management. Earthquake sustainability, and in a more general sense ERnZEBs, goes beyond this, requiring the following: the choice of highly recycled materials, durability, efficient use of structural, recycled materials exploiting their potential capacity, awareness of geological and local geotechnical soil foundation conditions, choice of efficient foundation systems, selection of structural systems that offer mitigation of displacements, equilibrated structural conformation layouts, components combining different functions (i.e., structural and energetic, energetic and mechanical, etc.), selection of details that minimize maintenance and repairs, easy erection and demolition, structural repairability following an earthquake, detailing by considering the disassembly and reuse of materials or elements. Certainly, apart from the others, we do not forget that everything starts with the architecture synthesis. Therefore, the functional adaptability of a building facility is of primary importance; practically all the aforementioned attributes will be maximized if the architectural layout permits the change of use and the possibility of renovation.

The drivers of sustainability, specifically, the strategy of reduce, reuse, and recycle, (reduce the production of construction materials, reduce the waste, reuse all the building components and elements, recycle everything from a building facility), within the framework of seismic action, are discussed below and further explained according to ERnZEB perspectives.

2.1. Reduce

Addressing the issue of structural material reduction, for the construction of an earthquake-resistant building (and, in a more advanced version, an earthquake resilient building structure), one can easily observe a controversial relationship between the first sustainable rule and the construction of a new building after a catastrophic earthquake (or the obsolescence of an existing building after a catastrophic seismic action). Systematically, after each strong earthquake, the codified seismic forces increase; the dimensions of the structural elements increase, consequently the consumption of building materials also goes up. Such an example is the case of Romania. For the capital city of Bucharest, from 1963 until now, the seismic design acceleration has increased 12 times, while for other county cities, this increase achieved 4 to 10 times [23]. It is a typical case for every earthquake prone country (Greece, Italy, Turkey, Japan, USA, New Zealand).

Another debatable issue is the well-established use of the behavior factor q (or response factor R according to US practice). For instance, in agreement with the forced-based design in EN 1998:1-1 [24], for the low ductility level, the q-factor is equal to 1. This fact leads to a structure that is designed elastically (of course without ductile detailing, as prescribed in the respective code), and it is not permitted to be applied in high seismicity areas. For a high ductility level, corresponding to a dual frame with a regular layout and cross section, the q-factor attains a value of 4.95. This means that the elastic design force is reduced approximately five times (strictly respecting ductile detailing). Evidently, in a disastrous earthquake, life safety would be protected; however, with so much damage, the building must be demolished. This was demonstrated by the New Zealand earthquakes [15]. Overall, the goals of sustainability are at the opposite end. A concept to design with a q-factor equal to one or to one and a half, always respecting the ductile detailing, will lead to a sustainable ERnZEB. According to unpublished studies of the authors, the average cost increase will be of the order of 20–25% (for a spectral acceleration of 0.36 g). Overall, an earthquake sustainable proposal occurs when we use a force based design to perform an elastic analysis and design with a q equal to one, or alternatively one and a half, and further on to respect the material, section, and member ductility and detailing. It is a pragmatic way of designing building until a resilient earthquake design, based on accepted target performance levels of drift, plastic rotation, crack width, accumulated deformation, and residual deformation, is developed.

Looking from a general perspective, the solution to this problem revolves around two axes. The first one is to give special attention at the phase of preliminary design, looking for an efficient conformation (suitable systems of foundation, positioning of structural walls at all principal directions of action, balanced layouts against torsion, etc.). A proper structural conformation saves lives, minimizes structural and non-structural damage, and protects properties; therefore, it reduces demolition cases, material waste, and building materials used for repair or strengthening. In many cases, this cannot be applied as desired by the structural engineer; this is due to architectural constraints. This last statement would be avoided if the architects would take into consideration the basic principles of seismic design and seismic urban planning in the same manner as sustainability.

The second axis moves toward the application of elements that change the dynamic characteristics of the building facility (i.e., base isolation) and/or control the behavior with passive damping (i.e., viscous, friction dampers, etc.), semi-active or active systems [25]. An illustrative example of the base isolation approach, along with an efficient energy design, was applied for the reconstruction after the L' Aquila earthquake, 2009, Italy, [26].

2.2. Reuse

This second principle of sustainability is twofold: (i) it is connected to a greater extent with existing building facilities, and (ii) the same ones, although after an earthquake. The concept of reuse must be related with another rule of 3 Rs, namely, with the Rehabilitation, Restoration, and Renovation.

From a structural point of view, the task is to retain the load-resisting system, LRS. If we have an existing building, the target is to strengthen the existing one by using the concept adapted from UNISDR to "*build it back better*" [27]. In the event that we have a building under construction, the issue is to employ structural prefabricated members (from steel, reinforced concrete, or timber) and, under certain conditions, also reuse the existing foundations (i.e., introduce micropiles, change a pad foundation system to a raft foundation, etc.).

From another perspective, designers for new buildings should already be thinking about the deconstruction of a structure. In an undamaged condition, it is relatively easy. In an earthquake-resistant environment, it is difficult to think about it. However, if the capacity design is used according to structural hierarchies, then the designer would save some members without damage, where they would be recovered and reused. Practically, this is difficult to achieve in the hard conditions after a catastrophic earthquake; as a consequence, the seismic design should be focused to generate structures that will respond elastically. To this end, one can mention that elastic stiffness is a structural property of a mechanical system that is reclaimed. The ductility is used once, and after a severe seismic action is “consumed”, producing damage; therefore, it is not reversible, and as a matter of fact, it is not a structural attribute that leads a member or a structure to be reused. Speaking in a figurative sense, ductility is not “materially sustainable”, although it must be recalled that, due to its force, redistribution and deformation capacity lead to lives being saved.

2.3. Recycle

To recycle is not to reuse. The waste materials are converted into new ones and not transformed. Thus, the recycling process is strongly related to building materials. At the same time, the topsoil from building excavations will also be put into service for landscaping works.

For earthquake-resistant purposes, steel structures represent a viable solution due to their complete recyclability, reduced weight, strength and ductility, architectural flexibility, dry construction, capacity of dissembling and reuse. It was the building material of choice for the reconstruction of Christchurch, following the 2010–2011 series of earthquakes that completely closed the operations in the Central Business District [28]; see **Figure 2**. Additionally, steel structures after major worldwide earthquakes behaved excellently, presenting only local failures and not global building collapses [29].

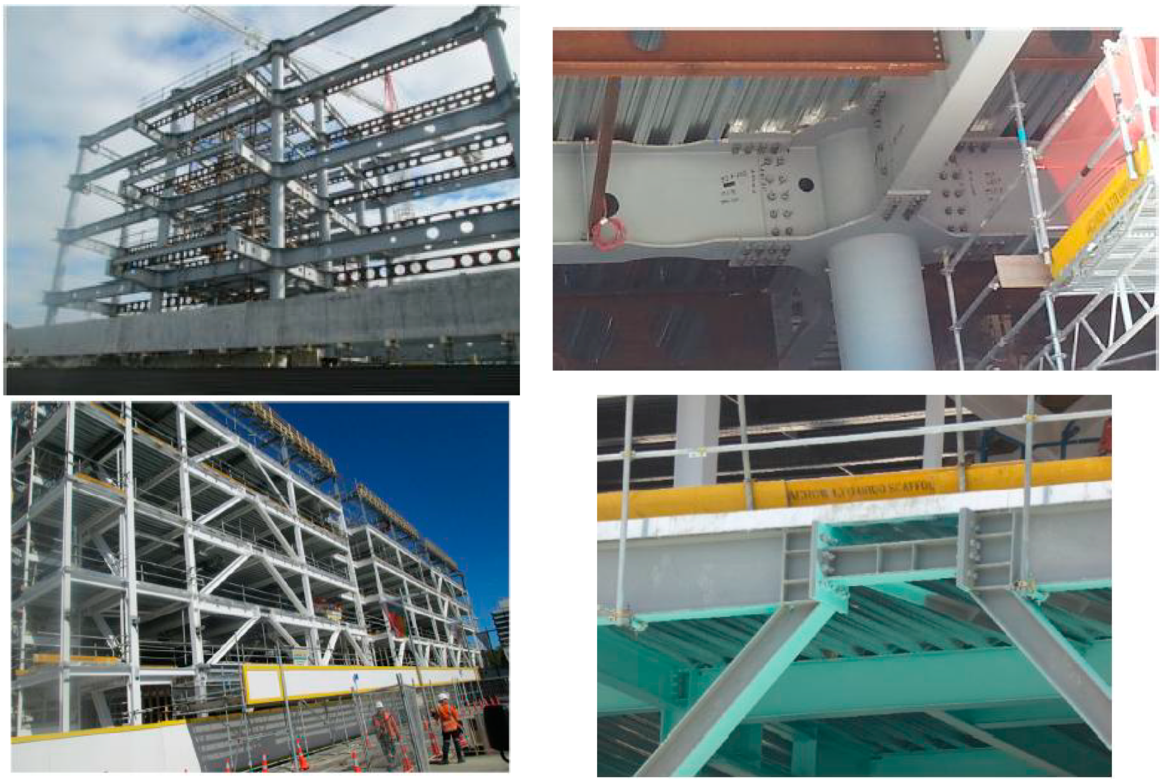

Figure 2. Reconstruction of Christchurch CBD using steel structural solutions [28].

A promising solution in the near future will be the construction of multi-story timber buildings, which are a recycle and sustainable solution for both the environment and human wellbeing. Structurally, it is similar to structural steel; however, it is a brittle material. Due to the fact that tall timber buildings have not been tested in strong earthquakes, investors and private owners are conservative about investing in or buying such buildings. Nevertheless, great research efforts are performed in order to better understand the cyclic behavior and, further on, to produce reliable codes that will open the door for the construction of multi-story building facilities [30][31][32]. Currently, cross laminate timber panels are used for both the seismic and energetic improvement of existing reinforced concrete buildings [33] and can also be applied to steel buildings.

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