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Application of steel in refurbishment of earthquake-prone buildings

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Subject review

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Refurbishment of existing buildings has become an increasingly topical issue in recent years. The recent Zagreb earthquake has also increased public awareness about the issue of sensitivity of old buildings to seismic loads. Steel plays a significant role in all aspects of refurbishment as it offers reliable rehabilitation and retrofitting solutions. The paper provides an overview of refurbishment methods with an emphasis on the assessment procedure for existing buildings, and methods for their seismic retrofitting using steel. Solutions that use new steel elements or improve the properties of existing ones are discussed, and some innovative retrofitting systems are highlighted.

Key words:

refurbishment, steel, earthquake, condition assessment, structure retrofitting

Pregledni rad

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Primjena čelika kod rekonstrukcije zgrada osjetljivih na potres

Rekonstrukcija postojećih zgrada je aktualna tema posljednjih godina. Nedavni potres u Zagrebu senzibilizirao je i javnost na problematiku osjetljivosti starih zgrada na seizmička djelovanja. Čelik ima značajnu ulogu u svim aspektima rekonstrukcije jer pruža pouzdana rješenja za sanacije i ojačanja. U radu je dan pregled metoda rekonstrukcije s naglaskom na postupak ocjenjivanja stanja postojećih zgrada i metode njihovog seizmičkog ojačanja čelikom. Obrađena su rješenja koja koriste nove čelične elemente ili poboljšavaju svojstva postojećih te su istaknuti i neki od inovativnih sustava ojačanja.

Ključne riječi:

rekonstrukcija, čelik, potres, ocjena stanja, ojačanje konstrukcije

Übersichtsarbeit

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Anwendung von Stahl beim Wiederaufbau erdbebenempfindlicher Gebäude

Die Rekonstruktion bestehender Gebäude war in den letzten Jahren ein aktuelles Thema. Das jüngste Erdbeben in Zagreb hat die Öffentlichkeit auch für das Problem der Empfindlichkeit alter Gebäude gegenüber seismischen Einflüssen sensibilisiert. Stahl spielt bei allen Aspekten des Wiederaufbaus eine wichtige Rolle, da er zuverlässige Lösungen für die Sanierung und Bewehrung bietet. Die Arbeit bietet einen Überblick über Rekonstruktionsmethoden mit Schwerpunkt auf dem Prozess der Bewertung des Zustands bestehender Gebäude und Methoden ihrer seismischen Bewehrung mit Stahl. Lösungen, die neue Stahlelemente verwenden oder die Eigenschaften bestehender Elemente verbessern, werden behandelt und einige der innovativen Bewehrungssysteme hervorgehoben.

Schlüsselwörter:

Wiederaufbau, Stahl, Erdbeben, Bewertung des Zustands, strukturelle Bewehrung

1. Introduction

Refurbishment of old buildings and preservation of cultural heritage are gaining in significance. These activities are equally relevant in masonry, reinforced concrete, and timber structures. The need for refurbishment, which also includes structural strengthening, is present in many older buildings. This need often arises from damage caused by atmospheric actions or earthquakes such as the one that hit Zagreb on 22 March 2020, causing damage to numerous structures, mostly old masonry buildings in the city core, and pointing to the importance of preventive measures of strengthening of the existing buildings.

Furthermore, older buildings that have not been damaged by destructive actions can be refurbished in order to allow change of occupancy, to provide additional space, to modernise the building, or simply to respond to the need for strengthening. It is often less expensive to refurbish the existing structure than to build a new one. Also, the refurbishment of existing structures with steel contributes to the preservation of cultural heritage because it does not interfere with the appearance of the building and also constitutes a sustainable construction practice [1-3].

Refurbishment of existing structures is an extremely demanding process because most of the structures are more than a hundred years old, and the need for refurbishment is only rarely covered in the original design. Even if it is covered, it is impossible to predict in original design all subsequent structural requirements, such as the installation of modern air conditioning systems, telecommunication networks, and various other installations and amenities. Also, many older buildings are part of the protected cultural heritage and any kind of intervention on those structures requires interaction and consultation with competent historic preservation offices.

In any remedial or refurbishment work, an initial assessment of the existing structure needs to be carried out [1] primarily to preserve human lives, and then to provide the basis for a high-quality refurbishment project. Old building refurbishment methods differ depending on the building material used, but also on the type of building, i.e. whether it is an 'ordinary' building or a building that is a part of the protected cultural heritage. In any case, steel as a material can provide numerous advantages in the refurbishment of old buildings, both in temporary works that primarily ensure the safety of the structure, and in works of a more permanent nature. Because steel elements are delivered to the construction site as finished products, spatial requirements for installation are extremely low, which is of great importance given that construction sites of existing buildings are mostly spatially limited. Steel is a material with an extremely high strength-to-weight ratio. Therefore, the installation is fast and rarely requires the use of heavy lifting equipment while an increase in self-weight of structure due to reinforcing elements is negligible. The speed of construction is particularly significant in evacuated residential buildings where the return of the occupants is of great importance. Also, steel can instantly transfer the load without the need for additional support and eliminates all wet construction phases, which is why disruption of normal life inside the existing building is reduced to minimum. Furthermore, steel is a material with a high level of ductility, which is one of the most important properties for ensuring seismic resistance of structures. This fact has been proven during numerous past earthquakes in which steel structures suffered much less damage compared to reinforced concrete and masonry structures.

It should be noted that each manufacturer has to meet numerous requirements prescribed by the EN 1090 standards when designing, manufacturing and testing steel products in order to obtain a 'Declaration of Performance' and CE certificate. Otherwise, the manufacturer cannot place its products onto the European Union market. This guarantees a high level of reliability of basic steel products for the construction of new steel structures, as well as for refurbishment of existing buildings.

This paper provides an overview of various steel-based refurbishment methods for existing buildings. Examples of steel application in the refurbishment of masonry, reinforced concrete, and timber structures are presented. Special emphasis is placed on seismic retrofitting of existing structures through addition of new steel elements or improvement of existing elements using steel. Some innovative strengthening methods for existing structures, increasingly applied in practice, are also highlighted. To emphasise the importance of assessing existing structures prior to development of an actual refurbishment project, an overview of modern methods used in such procedures is also provided in the paper.

2. General application of steel in refurbishment of existing buildings

2.1. Introduction

The above-mentioned advantages of the use of steel material are a main indicator of its various uses in the construction of new, and in refurbishment of existing buildings. Also, due to wide availability of steel products on the market, the possibility of adapting steel to any refurbishment-related requirement is practically unlimited. Finally, it is also important to note that the application of steel, especially in historic buildings, is almost the only solution that allows reversibility of the refurbishment process, i.e. removal of elements without damaging the existing building. In general, the term refurbishment implies works on existing buildings which, depending on the importance of their objectives, can be divided into [1, 4]:

- works that primarily ensure safety,
- rehabilitation works,
- strengthening/reinforcement works,
- restructuring works, i.e. works related to change of use of buildings and building additions.

Works primarily ensuring safety involve solutions of temporary nature, the aim of which is to ensure only short-term safety of people inside the building and in its immediate vicinity. These actions are undertaken when the building has become unsafe due to damage from accidental or excessive loads, due to deterioration resulting from the lack of maintenance, but also before the beginning of works of more permanent nature.

Rehabilitation includes activities aimed at eliminating the damage in order to restore previous condition of the building, i.e. to ensure the level of structural resistance which existed before the damage occurred.

On the other hand, structural strengthening works involve improvement of structural properties in order to meet new requirements arising from the change in intended use of the building (e.g. increase of service load) or the change in building site classification (e.g. the site is classified as being seismically active). Therefore, we distinguish between strengthenings that do not affect seismic resistance of buildings (Section 2.2) and those that are carried out in order to increase seismic resistance of buildings (Section 4).

Restructuring works include partial or complete modifications in terms of functionality and spatial dimensions (volume), changes of original features of the building, including partial or complete modifications of the building's structural system. These works usually involve replacement, insertion, addition or lightening of a single part or the entire structural system in order to achieve the ultimate building refurbishment goal.

2.2. Rehabilitation and strengthening of buildings

Although there is a clear difference between the objectives of rehabilitation and strengthening, the procedures for their implementation are often very similar, and sometimes even completely identical. Unlike rehabilitation, strengthening is carried out to ensure a higher level of reliability. These works are either performed on individual structural elements or on the entire structure, and should not have a significant impact on the structural system itself, i.e. on its load-bearing concept, because such scope of work does not involve major changes in the distribution of building mass and/or stiffness. Also, it should be noted that the rehabilitation and strengthening procedures mentioned in the scope of this section are not aimed at increasing seismic resistance of buildings.

Damage to masonry and reinforced concrete buildings can be repaired using steel rings, or steel strips, angles, and C profiles. An increase in load-bearing capacity can also be achieved if appropriate prestressing is additionally applied. If, on the other hand, there is a need to take on a significant vertical load, masonry structures can be strengthened with additional steel columns that can be easily connected to or inserted in the existing structure (Figure 1.a).

In the case of floor structures, rehabilitation solutions differ depending on the side the floor structure can be accessed from. For underneath access, solutions involving addition of different steel profiles or plates are most often used, which, given their great variety, can be appropriately selected for any purpose (Figure 1.b). When access from below is impossible, or when it is necessary to preserve the original appearance, strengthening activities are performed from above, again, using steel profiles (Figure 1.c).

Wooden roof trusses can be repaired by adding steel plates at the joints or along the elements. This solution is extremely complex and is therefore rarely applied. A better solution would be to completely replace wooden truss with steel one and, if possible, to cover the structure using profiled steel sheets. Replacement of roof structures is often performed in sacral buildings, where in many cases such a structure, besides having the main function to assume vertical loads acting on the structure, can also serve as a horizontal diaphragm, which is particularly important in seismically active areas.

2.3. Insertion and addition of structural system

Although service life of buildings is not unlimited, their load-bearing system, unlike other parts and systems in the buildings, is expected to last longer and, for this reason, the need to provide for its adaptability is very important, not only at the refurbishment phase, but also at the phase of initial design. This requirement should be taken into account already during the design phase of new buildings so that necessary alterations can be made without difficulties during subsequent refurbishments. Also, in many European cities, due to the lack of space, existing buildings need to be upgraded and adapted to new social and economic needs [2]. Solutions to these problems can be found using two approaches: insertion in the existing load-bearing systems, and making additions to such systems. As these approaches optimise land use, they can also be classified as sustainable types of construction work [2].

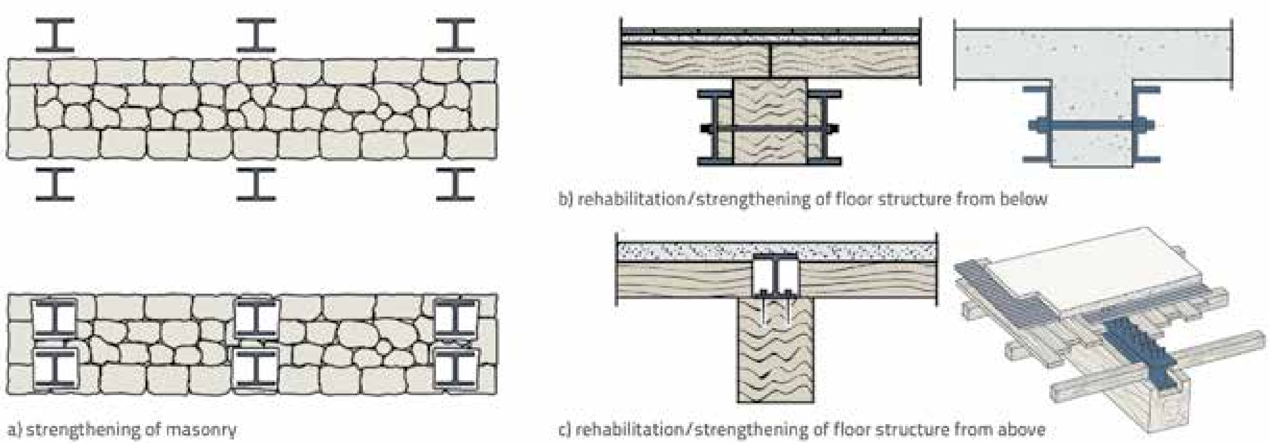

Figure 1. Examples of rehabilitation and strengthening [4]

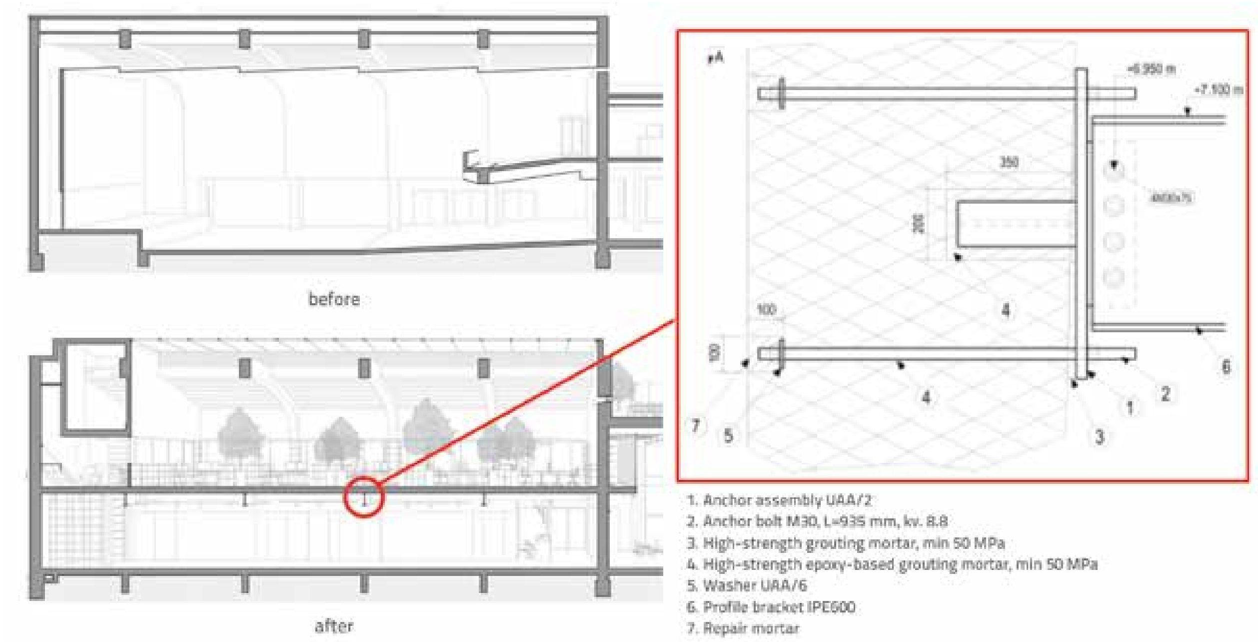

Figure 2. Conversion of former Urania cinema building into new office building for Studio 3LHD, Zagreb: a) Insertion of structural system to existing volume – longitudinal section before and after addition [5]; b) Joint detail solution: adding steel beam to existing RC column [6]

The insertion of either individual structural elements or the entire structural system involves integration within the existing volume, and results in an increase of the usable floor area or in the provision of some additional functions (e.g. elevator shafts or staircases). As the insertion works are limited with the existing volume, they are usually performed when converting old industrial halls into office or residential units, or in the case of a relatively large storey height (e.g. insertion of attic within the roof space). Thus the existing building of the former Urania Cinema in Zagreb has recently been converted into the office building for the Studio of Architecture and Urbanism - 3LHD [5, 6]. The central volume of the cinema is divided into two floors using a composite (steel-concrete) floor structure, as shown in Figure 2.a. Given the sufficient load-bearing capacity of the existing structure (RC frame with variable cross-sectional dimensions, 12.4 m in span, 10.8 m in height), it was possible to place the new steel girders (IPE 600, S355J2) directly onto the RC columns. The joint detail solution is shown in Figure 2.b.

On the other hand, additions increase usable space through a new volume, i.e. the original volume of the building is increased through horizontal or vertical additions. With horizontal additions, it is usually more important to pay attention to the aesthetic aspect and less to the structural aspect. In the case of vertical additions, it is necessary to assess the load-bearing capacity of the existing structure as well as the impact of the planned addition and, if necessary, certain steps must be carried out so that the additional load can be assumed. This is especially significant in seismically active areas where behaviour of the entire building depends on the newly added mass. The most favourable cases in terms of performance are those when vertical additions can be made without any or with only minimum interventions on the existing structure. This is usually the case with one-storey or two-storey vertical additions to an existing building where thin-walled steel profiles are used, which allow for an easy and quick installation due to high resistance-to-weight ratio.

Vertical additions can also include introduction of a significantly larger number of storeys, where it is often necessary to strengthen the existing structure or even add completely new supports for the added part of the structure. Therefore, vertical additions are mostly carried out using steel and composite structures which ensure the most favourable self-weight-to-strength ratio. For example, vertical addition to a building in Toronto (Canada) was originally planned as a reinforced-concrete structure. This idea was subsequently abandoned and the addition was constructed in steel, therefore allowing for the addition of eight instead of four storeys [4]. In our country, one of the most renowned vertical addition is that of the Euroherc Office Building in Zagreb (Figure 3), where a five-storey upgrade was carried out partly as a steel structure and partly as a composite (steel-concrete) structure [7].

Figure 3. Vertical addition – Euroherc Office Building in Zagreb

2.4. Lightening of structural system

In contrast to the insertion and addition work, there is also work that is aimed at reducing self-weight in order to reduce load imposed on the existing load-bearing system. This can be achieved by using new and lighter materials during realisation of floor structures, roof structures, or other structural elements. Heavy wooden floor structures are often replaced with steel I profiles on which profiled sheet metal is laid (Figure 4.a), or, as already mentioned, existing roof structures are replaced with steel roof trusses (Figure 4.b).

Figure 4. Lightening of structural system: a) replacement of a heavy wooden floor structure with composite structure; b) replacement of wooden roof truss with steel truss

2.5. Gutting of structural system

It is becoming increasingly common, for architectural or urban reasons, to keep the external facade of a building while adjusting the interior for some functional reasons. In such cases, some parts of the interior, or the entire internal structure of the building, need to be replaced. Such works, apart from being extremely expensive, are also very complex. All phases of construction work must be carefully considered, during which façade stability must be ensured with a temporary structure, which must not interfere with and obstruct realisation of other works in the refurbishment process. The advantage of using steel in such works is that steel can assume loads immediately after installation. At the same time, there is no creep and shrinkage that could create problems at points where the new and old parts of the structure meet. Also, the use of composite floor structures allows for lower overall height of such structures, which makes them easier to fit into the existing floor heights. Finally, high strength exhibited by steel results in the provision of more usable space within the limited floor area. An example of conversion of an industrial reinforced-concrete building into a school hall by changing the load-bearing system is shown in Figure 5.

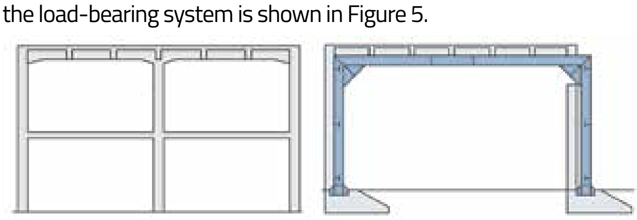

Figure 5. Gutting of the structural system [4]

3. Seismic assessment of old buildings

3.1. Assessment procedures

Assessment of structural seismic characteristics is a key topic in the process of building retrofitting. The aim is primarily to reduce the risk of loss of human lives, but also to reduce social and economic impacts in the event of global or partial collapse. Today, as a response to such needs, designers have at their disposal various standards and guidelines, which include numerous approaches and tools that have been developed over time to correctly design and execute retrofitting activities, while increasing at the same time structural reliability [8-11]. It is important to note that, in many cases, these standards and guidelines do not provide designers with all necessary data, which is why integration of different standards in a particular operational procedure is often needed [12].

Assessment approaches are generally defined in the scope of the Performance-Based Earthquake Engineering (PBEE). In such approaches, the condition of a structure is determined based on comparison of the demand and capacity of an element or structure. The demand can be defined as the maximum requirement imposed by actions or loads in terms of stress or strain/deformation. At the same time, the mentioned capacity is also a demand parameter that the structure can fulfil. For example, according to [8], the demand is organised as a multi-level framework in which each level is associated with different intensity of seismic action, and each capacity level with a separate limit state.

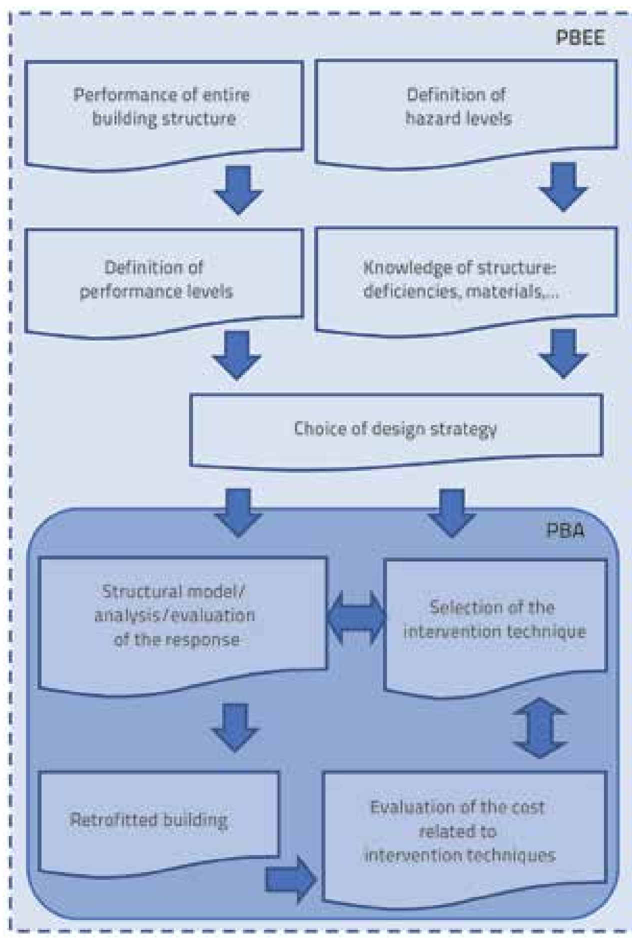

Figure 6. PBEE framework and PBA sub-framework

PBEE is generally based on the definition of different levels of structural performance, identified as damage levels of primary or secondary structural elements. These levels are reached when the building is subjected to different earthquake intensities, i.e. peak ground accelerations. Considering also operational aspects regarding practical application of the PBEE conceptual framework, which introduces the Performance-Based Assessment (PBA), it is possible to individualise a general flowchart, as shown in Figure 6 [12, 13].

The flowchart given in Figure 6 refers to retrofitting of existing structures in the event of an earthquake. As can be seen from the flowchart, the PBA represents the operational core within the PBEE in which modelling techniques, numerical analysis, and technical aspects are interrelated, in order to arrive at final intervention techniques. Other aspects represent the general set-up of the retrofitting that determines design options derived from safety levels and minimum structural behaviour requirements [12].

The choice of design strategy is essential in this procedure, cf. Figure 6. The design strategy is based on the hazard level, performance level and information about the existing structure. The strategy is used to create a FE structure model to assess static and seismic demands for individual structural elements. Accurate modelling of mechanical properties of materials and geometry of the building, coupled with the use of available analyses (linear or nonlinear), enables determination of structural deficiencies (local and global). Uncertainties related to the data required in this procedure are evaluated according to [8] using specific levels of knowledge. The damage simulation analysis results can be compared with actual damage to the building, in order to confirm accuracy of the model. The next step is to propose a retrofitting solution (presented in Section 4), whose effectiveness is assessed in the final step.

3.2. Deficiencies of old buildings

Structural systems of many old buildings are not adequately designed and contain a number of irregularities in terms of geometry, strength of material, or rigidity, depending on their floor plan or height. In many cases, these buildings have been subjected to previous earthquakes or other accidental events with unknown effects. Also, numerous assumptions and simplifications were adopted during their design and construction, where seismic resistance was not considered at all, while non-seismic actions were covered by traditional construction rules. Computers and spatial models were not used, and most elements were considered independently of the system. In addition, parameters necessary for ensuring acceptable seismic behaviour of structures, such as ductility and capacity, were ignored. Also, seismic design of structural details was not defined in regulations and standards applied to such buildings. In the light of the above, it can be stated damage caused by a possible earthquake may generate the need for significant repairs, as has been witnessed after the recent earthquake in Zagreb.

The assessment and potential retrofitting procedures are exposed to numerous uncertainties which, according to HRN EN 1998-3 [8], are expressed through the already mentioned levels of knowledge. Depending on the level of knowledge, this standard encompasses uncertainties through various sets of material and structural safety factors, as well as through various analysis procedures, depending on the completeness and reliability of available information. To be able to select a suitable retrofitting solution, it is necessary to conduct preliminary assessment of deficiencies associated with the considered building. Thus, for example, according to [12], deficiencies of a building structure can be assessed based on the behaviour of:

- structural elements of which the structure is composed (point deficiency).
- structural subsystems composed of structural elements depending on their role in the transfer of load within the structure (local deficiency).
- structural topologies in which individual subsystems are incorporated (global deficiency).

When assessing shortcomings of an individual building, structural subsystems should be divided into roof systems and floor systems, vertical load transfer systems, which include all structural elements supporting the roof and floor structures, and a foundation system, which includes all structural elements that transfer loads to the

Figure 7. Typical building damage in Zagreb after the earthquake: a) Damage to gable wall; b) Diagonal wall cracks; c) Vertical wall cracks

ground including the ground itself. Figure 7 shows typical damage to vertical systems on some buildings damaged in the Zagreb earthquake. Based on systems listed in [12], it is possible to describe deficiencies and typical problems of existing buildings, as described below.

As each structural system consists of different structural elements, it is possible to identify critical areas within the structure. Regarding the role of elements in the structure, it is appropriate to classify them into load collecting elements and load supporting elements. Accordingly, load collection areas and load transfer areas are distinguished, and can be classified into surface areas, linear areas and point areas, while structural elements are divided into 1D elements (beams, columns, arches, bars, etc.), 2D elements (walls, slabs, vaults, etc.) and 3D elements (rigid joints, short cantilevers, foundations, anchor blocks, foundation soil, etc.).

In order to identify critical areas in a structural element and classify possible problems, it is necessary to determine the demands and capacity of the element. The demands represent the maximum stresses and strains resulting from seismic action, while the capacity represents the maximum stresses and strains that the element can withstand. In the case where the ratio between the demand and capacity is close to 1 the area can be considered as critical. When such areas are strengthened using various retrofitting methods, demands or capacities of these areas can be either reduced or increased.

If damage occurs in multiple locations, local or global failures are possible. In this case, it is necessary to identify potential paths in the assessment procedure that, from the damage of single element, could lead to local or global failures.

Identification of structural deficiencies requires a detailed study of geometry data, structural details data, and material mechanical properties data. A brief overview of these activities is given in the next section.

3.3. Geometry, structural details, material characteristics and tests

As is the case with most existing buildings, the availability of data on the geometry, structural details and material properties is rather limited. For this reason, it is necessary to collect data from various sources including available documentation related to a specific building, and relevant standards and regulations. Furthermore, for the most reliable assessment, it is necessary to conduct detailed inspections and field tests and, if needed, laboratory tests on samples taken from different parts of the building. When considering global behaviour of a structure, the data that can significantly reduce inherent uncertainties may prove quite useful. Non-destructive test methods are particularly important in this respect. For example, dynamic structural parameters collected in this way provide a basis for evaluation of the numerical structural model accuracy and for determination of uncertain structural parameters, such as the modulus of elasticity and soil characteristics. Details of these procedures can be found in relevant standard [8], and in specific examples from literature [14-17]. Test procedures, inspection lists, and other data collected for this purpose, must be documented and referred to in the retrofitting design documentation [8].

Based on the reliability of the data, HRN EN 1998-3 [8] defines the already mentioned levels of knowledge as related to the permitted calculation types and the corresponding confidence factor values. The factors used for determining the levels of knowledge are: geometric factors, structural details, and materials. Geometric factors are related to geometric characteristics of structural elements as well to those of non-structural elements that can affect structural behaviour. Structural details are related to the percentage and design of reinforcement in reinforced concrete, connections and joints between elements and floor structures to elements collecting horizontal forces, and also to the adhesion and joint details in the masonry, and masonry strengthening details, if any. Materials are related to their mechanical properties. More details regarding determination of knowledge levels can be found in the HRN EN 1998-3 [8].

Depending on the knowledge level, the measured mean values of material properties are either divided or multiplied by confidence factors. In the case where the system capacity is checked against the demands, a division of material properties is applied. On the other hand, multiplication of material properties is used when determining capacities of ductile components that transmit action effects to brittle components or mechanisms.

3.4. Demands for structural behaviour and compliance criteria

Assessment is a qualitative procedure that is used to control whether an existing undamaged or damaged building will meet the boundary condition demand corresponding to the considered seismic action. In this procedure, seismic action corresponds to the previously defined demands set for structural behaviour. The assessment procedure itself is carried out by methods defined in HRN EN 1998-1 [18] which are adapted to certain assessment demands formulated in HRN EN 1998-3 [8]. HRN EN1998-3 defines the demands in the form of the following three limit states of building behaviour:

- *Damage Limitation* – DL,
- *Significant Damage* – SD,
- *Near Collapse* – NC.

These limit states are related to mean return periods (MRPs) which correspond to certain probabilities of exceedance. In the case of DL, the MRP is 225 years with a probability of exceedance of 20 % in 50 years, in SD the MRP is 475 years with a probability of exceedance of 10 % in 50 years, and in NC the MRP is 2475 years with a probability of exceedance of 2 % in 50 years.

Compliance with the requirements is achieved by accepting seismic action, calculation methods, verification procedures, and structural details elaboration procedures that are related to individual materials (concrete, masonry) [8]. UIn this procedure, it is recommended according to [19, 20], to introduce probabilistic analysis based on a logical tree in order to make it easier for the designer to identify and define possible situations that lead to collapse.

Linear and nonlinear methods can both be used for structural analysis. However, the application of linear ones is defined by certain conditions. For example, in the case of masonry structures, which represent the majority of those damaged after the earthquake in Zagreb, the application of linear methods, static and multimodal, is limited with a number of conditions as stated in [8, 13, 20]. If these conditions are taken into account, it can be assumed that the application of linear methods will not be allowed in the majority of cases.
Compliance is controlled through application of elastic seismic action following the defined return periods for each limit state. It is also possible to use the procedure with a behaviour factor taking into account certain restrictions defined in HRN EN 1998-3 [8]. In this procedure, it is necessary to make a distinction between ductile and brittle structural elements, where ductile elements are checked against their deformation ability, while the brittle ones are checked against their strength. Details on compliance requirements concerning each limit state are defined in Section 2 of HRN EN 1998-3 [8].

4. Possibilities for seismic retrofitting of old buildings using steel

4.1. General

In general, the seismic retrofit design procedure includes the following steps: conceptual design, analysis and verifications [8]. The focus of this section is to provide description of various steel construction techniques used in seismic rehabilitation rather than to give complete guidance on the far more subtle process of developing and designing complete rehabilitation schemes. Although the latter may be useful to engineers inexperienced in seismic retrofit or seismic design in general, the schematic design process for seismic rehabilitation is complex and often involves more art than science [21].
In order to upgrade the existing structures, various retrofit techniques are continuously being developed. Steel based solutions appear to be more competitive in terms of performance, applicability, and reversibility [12].These solutions either target to upgrade performance of existing elements, such as beams and columns, in terms of strength, stiffness or ductility, or to create a completely new lateral load resisting system, or even to upgrade the existing infill walls so that they behave as reliable resisting systems. Moreover, in special cases, techniques that involve base isolation or dampers can be used, but their application is rather unlikely in commonly encountered residential structures [22].

4.2. Classes of retrofit measures

In order to design an efficient retrofit scheme, it is necessary to have a thorough understanding of the expected seismic response of existing buildings, as well as of all their deficiencies. In most cases, the primary focus for the determination of a viable retrofit scheme is on vertically oriented components (e.g. columns, walls, braces, etc.) because of their significance in the provision of either lateral stability and/or resistance to gravity load. Deficiencies in vertical elements are caused by excessive inter-story deformations that create unacceptable force or deformation demands. However, depending on the type of building, even if walls and columns are adequately designed for seismic and gravity loads, partial or complete collapse may occur in an earthquake if building components are inadequately connected. Moreover, as noted during the last strong earthquake that struck Zagreb on 22 March 2020, another weak point of the structure, primary related to old masonry buildings, is inadequate rigidity of horizontal diaphragms (wooden floors).
In the traditional sense of improving performance of existing structures, there are three basic classes of measures that are taken to retrofit a building:

- Add elements - usually to increase strength or stiffness.
- Enhance performance of existing elements - increasing strength or deformation capacity.
- Improve connections between components - so that individual elements do not detach and fall; a complete load path is thus provided, and the force distributions assumed by the designer is ensured.

The types of retrofit measures often balance each other in a way that employing more of one will mean that less of another is needed. It is obvious that providing added global stiffness will require less deformation capacity for local elements (e.g. individual columns), but it is often less obvious that careful placement of new lateral elements may reduce connectivity issues such as diaphragm deficiency. Important connectivity issues such as wall-to-floor ties, however, are often independent and must be adequately considered. The classes of retrofit measures are discussed in more detail below.

4.3. Adding new elements

This is the most obvious and most general class of retrofit measures. In many cases, new steel and/or composite shear walls [23, 24], braced frames, moment frames, or their combinations [25], are added to an existing building to mitigate deficiencies in global strength, global stiffness, configuration, or to reduce diaphragm span. New elements can also be added as collectors to mitigate deficiencies in the load path.
Retrofit schemes have been developed as a balance between addition of new elements and enhancement of existing elements in a manner that best meets particular socio-economic requirements. Either method, addition of new elements or enhancement of strength of the existing ones, could create a load transfer issue. The designer must make sure that the new loads that are redistributed to these elements can be transferred to them via other existing components. Therefore, solving the deficiency problem in global strength or global stiffness may cause a deficiency in the load path that initially did not exist.
The use of steel braces is very effective in strengthening both masonry and reinforced concrete structures against earthquakes [4]. Shear walls with lattice infill have two purposes: increase resistance of the structure to horizontal forces and balance

Figure 8. Buildings retrofitted with external steel braces

Figure 9. Steel tie rods: a) Example of old and recent tie rods (above old ones); b) Tie rod anchorage detail; c) Typical mode of failure

distribution of internal rigidity with respect to shear centre in order to minimise dangerous torsional effects. In masonry structures, steel braces may be located inside or beside the masonry wall and must be connected to floor structures. On the other side, in reinforced concrete structures, steel profiles are connected to the perimeter of the reinforced concrete frame meshes, within which cross diagonals are arranged. Examples of building retrofitting with external steel braces are given in Figure 8.

Relative rigidity of unretrofitted structures and new steel bracing are an important factor that should be taken into consideration. In an earthquake, cracking is expected to occur in the original masonry structure and, after sufficient cracking has occurred, the new steel system will have comparable stiffness and be effective [26]. In general, a vertical stabilisation system with diagonal braces improves lateral in-plane resistance of the retrofitted wall by 4.5 times [27], whereas in the case of infill panel, the system increases the in-plane lateral resistance of the retrofitted wall by 10 times.

Steel tie rods can be used in several retrofitting applications for old masonry buildings [28]. For instance, they can prevent or at least decrease the probability of out of plane failure. Tie rods can also be used in arches to absorb horizontal forces, Figure 9.a. The application of horizontal tie rods to connect parallel walls at floor level is shown in Figure 9.b. Failure of the tie-rod anchorage after an earthquake, which occurred due to excessively small anchor plate area, is shown in Figure 8.c).

4.4. Enhancing performance of existing elements and connections

Instead of using retrofit measures that affect the entire structure, deficiencies can also be eliminated at the local level on existing components. This can be done by enhancing the existing shear or moment strength of an element, or simply by altering the element in a way that allows additional deformation to occur without compromising vertical load-carrying capacity.

As certain components of the structure will yield when structure is subjected to strong ground motion, it is important to recognise that preferred yielding sequence is always: beams yield before columns, bracing members yield before connections, and flexural yield occurs before shear failure in columns and walls. These relationships can be determined through analysis and can be controlled by applying local retrofit in a variety of ways. For example, see Figure 10.

Figure 10. Retrofitting reinforced concrete members using steel plates

Figure 11. Retrofitting timber floors using steel: a) retrofitting with steel ties arranged in crosses; b) connection between floor and masonry wall

Columns in frames and connections in braces can be strengthened, and shear capacity of columns and walls can be enhanced so as to be higher than the shear action that may occur due to achievement of flexural resistance.

Concrete columns can be wrapped with steel to provide confinement and shear strength.

Traditionally, masonry buildings have timber floors that are typically flexible. An increase in the in-plane stiffness of floors is an evident and most effective method of improving seismic behaviour of old masonry structures [4]. This happens mainly because an increase of in-plane stiffness of floors enables the structure to assume a box-like behaviour. This allows redistribution of horizontal forces between vertical structural members, but at the same time horizontal forces of failing walls and columns can be redistributed to the adjacent remaining vertical elements. Thus, by strengthening a floor, one has the opportunity to improve the behaviour and efficiency of the entire structure.

One of possible techniques is the idea of including horizontal braces composed of steel ties arranged in crosses, on the floor structure, as shown in Figure 11.a. Care must be taken to improve the connection between the floor and the masonry wall, which can be made with L-shaped steel sections, Figure 11.b. In contrast to the technique of composite wood-concrete deck, this solution does not significantly increase the mass of the floors and is also reversible.

The class of rehabilitation technique is almost exclusively targeted at mitigation of load path deficiencies. With the exception of collectors, a deficiency in load path most often results from a weak connection, rather than from a completely missing link. However, some poor connections, particularly between beam and supporting column, are not directly in the primary seismic load path but still require strengthening to assure reliable gravity load support during and after strong earthquake.

Appropriate systems for strengthening two traditional types of joints (rigid and pinned) by means of stiffening elements can be applied. In the case of rigid joints, the bending capacity is then improved. In the case of pin-ended joints, the integration of stiffeners is designed in such a way to introduce capacity required to resist bending moments, which is practically non-existent in the original joint. Lastly, deformation capacity can be enhanced locally by uncoupling brittle elements from the deforming structure, or by their complete removal.

4.5. Passive structural response control systems

Structural response produced by earthquakes can be controlled by means of various systems based on different concepts, such as by modification of masses or damping, as well as by production of passive or active counterforces [4]. In passive systems, which do not require an external source of power, properties of structures (period and/or damping capacity) do not vary depending on the seismic ground motion.

The use of passive control techniques in the refurbishment of existing buildings is a relatively new procedure. Although there are several different passive structural response control systems, the first significant applications in buildings were realised in Italy in the 1990s using oleo-dynamic dampers [4]. Innovative steel beam-to-column connections with friction dampers for dissipation of the earthquake input energy have recently been studied within the European research project FREEDAM [29]. The connections are designed in such a way to provide wide and stable hysteresis loops without any damage to steel plate elements. In addition, they are economically more viable compared to oleo-dynamic dampers.

5. Conclusion

Having in mind the goal of sustainable construction and preservation of cultural heritage, the issue of refurbishment of existing buildings has recently been gaining in significance. The recent earthquake in the city of Zagreb endangered local population and caused significant material damage, stressing the importance of structural rehabilitation and retrofit of old buildings. Accordingly, various methods of refurbishment of old buildings using steel are described, and a special emphasis is placed on seismic retrofit of existing structures. As initial assessment of existing structures before or after an earthquake is a necessary step in retrofit procedures, this paper also gives a brief overview of modern methods used in such activities. Based on the above, the following conclusions can be made:

- Various international recommendations for reconstruction work recognise that the use of construction methods of the past may no longer be appropriate or even possible. As an alternative to traditional methods, refurbishment methods using steel structural elements are recommended as they, *inter alia*, enable reversibility of the refurbishment process.

- Steel as a material presents numerous advantages over traditional methods of structural rehabilitation and retrofitting, including the use of prefabricated elements, speed and ease of construction, and elimination of wet construction phases. Also, due to high strength-to-weight ratio, the impact on an increase in self-weight of the existing structure is negligible, which is a key advantage, especially from the aspect of seismic resistance.
- Steel also offers the possibility of change of use and extension of the building through insertion of new structural elements or entire structure into an existing volume, or through addition of new vertical and horizontal volumes. In this way, land use is optimised, and so such approaches can be classified as a sustainable type of construction.

In addition to the above advantages, the use of highly reliable and ductile construction material, such as steel, ranks among the most effective ways to reduce material damage but, even more importantly, to save lives, during future earthquakes. Of course, the optimum can be achieved only if the reconstruction is carried out by engineers knowledgeable in modern steel-structure design procedures.

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