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Seismic Performance of Reinforced Concrete Buildings with Joist and Wide-Beam Floors during the 26 November 2019 Albania Earthquake

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Abstract: Beams with width greater than their depth and depth equal to the depth of the slab (concealed wide beams) are widespread in Reinforced Concrete (RC) buildings in Albania. A large number of RC buildings with wide beams were hit by a strong M_w6.4 earthquake on 26 November 2019. The earthquake hit two of the most densely populated areas in Albania and caused widespread damage to these buildings. This paper aims to provide an updated view on the seismic performance of buildings with wide beams in light of the new field data following the 26 November 2019 Albania earthquake. To this end, a thorough literature review including experimental and field observations from past earthquakes is presented and data from field visits in Albania are described. It was found that damage to the joists and wide beams themselves was limited, even when the buildings suffered significant non-structural or structural damage in other elements as a result of the earthquake. A discussion on the behavior of wide beam–column frames based on nonlinear structural analyses and tests from the literature is presented. Furthermore, the implications of the results of the analysis for the seismic performance of RC buildings are discussed and confronted with observations from the 2019 Albania earthquake. Based on the literature review, further experimental research on wide beams with longer and more realistic span lengths is recommended.

Keywords: wide beam; shallow beam; concealed beam; reinforced concrete; seismic performance; Albania earthquake; beam–column connection

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1. Introduction

For architectural and construction purposes, it is convenient to have a flat slab soffit which allows a free placement of partition walls and reduces construction time and costs due to the simple formwork. The most common solution (especially in low seismicity areas) is to use flat slabs, which are solid slabs directly supported on columns, without beams. A similar end result is achieved by a combination of beams that have depth equal to the thickness of the slab and ribbed or joisted slabs. To achieve the required moment capacity, the width of these beams is often greater than their depth. These beams are referred to as "wide beams", "concealed beams" or "shallow beams".

Wide beams are very popular in the Mediterranean region [1–3], which is a region with high seismic activity. In Albania, a combination of beams and one-way or two-way slabs with uniform thickness is the preferred slab system in multi-story reinforced concrete buildings. Two-way joisted slabs are typically used when the axial grid is close to square, whereas one-way joists are typically used when the slab is rectangular with ratio-of-side lengths above two. The voids between the joists are filled with lightweight material, typically polystyrene or lightweight clay bricks. The depth of the slab and beams

is typically between 20 cm (for short spans) and 30 cm, although a minimum thickness of 30 cm for primary seismic beams is required by the Albanian seismic design code [4]. A typical detail of the slab system commonly used in Albania is presented in Figure 1.

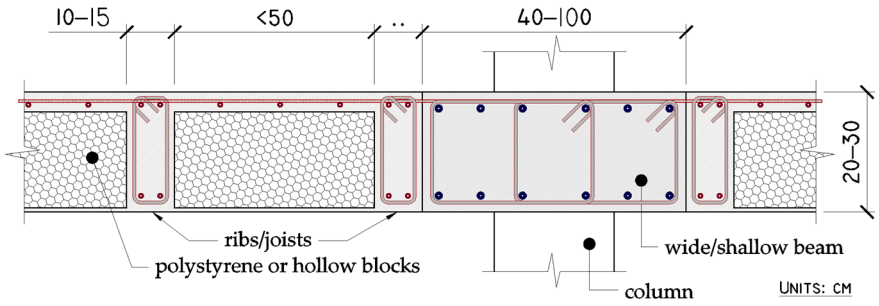


Figure 1. Typical detail of a wide beam and joisted slab used in Albania.

Photos of the wide beam–joisted slab system are shown in Figure 2. Figure 2a shows a slab under construction, with wide beams in two directions and a one-way joisted slab. Notice the flat formwork in Figure 2a (one of the main advantages of this system) and the dense shear reinforcement in the beams. It is common to have situations in which the width of the beam is greater than the dimension of the supporting column, which is sometimes not in accordance with the national seismic code requirements [4] regarding width and eccentricity: $b_w \leq 2b_c$ and eccentricity $e \leq b_c/4$. In many cases, wide beam–column frames are the only lateral load resisting system in RC buildings in Albania, although newer buildings typically have shear walls and/or perimeter moment-resisting frames. An example of a building under construction in Tirana with shear walls and wide beams is shown in Figure 2b.

(**a**) (**b**)

Figure 2. Wide beams in Albania: (**a**) photo during construction; (**b**) wide beams in a building with columns and shear walls under construction in Tirana.

The slab system shown in Figure 2 became popular in Albania after 1990. A large number of RC buildings employing this wide beam–joisted slab system were subjected

to the M_w6.4 26 November 2019 earthquake and a series of aftershocks in Durrës and nearby areas. The earthquake was the strongest in more than three decades, offering an opportunity to study for the first time the seismic response of wide beam–column connections with detailing and dimensions typical for Albania. In the meantime, the information gathered after this earthquake is potentially useful for other countries in which similar structural solutions are used. In this context, the purpose of this paper is to summarize the main observations regarding the seismic performance of wide beams during the 26 November 2019 earthquake in Albania and to compare them with observations from past earthquakes as well as the expected behavior based on experiments conducted in the past.

The paper contains six sections. After this first section, a literature review of the experimental work on the seismic behavior of wide beams is presented in Section 2. Observations from past earthquakes in other countries and from the 2019 Albania earthquake are summarized in Sections 3 and 4, respectively. Nonlinear pushover analyses for a case-study building in Durrës and experimental observations and findings are discussed in Section 5 with the help of an analysis of the yield drifts for beam–column connections from the literature. Finally, conclusions are presented in the last section.

2. Literature Review: Experimental Work

A variety of test configurations, specimen dimensions and reinforcement details were found in the literature. Tests of interior connections as well as exterior ones were found. The most common test setup for interior beam–column connections is the one shown in Figure 3a. This test setup is also one of the most common for slab–column connections under lateral loading [5]. For exterior connections, the setups shown in Figure 3b,c are the most popular. The experiments indicate that with the increase in the ratio between beam width and column width, the development of the full capacity of flexural plastic hinges is hindered by rebar slippage and torsional cracking in the transversal beam [6–10]. Tests show that the energy dissipation capacity of the connections is relatively low, the stiffness is low and the displacement at yielding is relatively large [1,6,11]. The latter means that damage limitation criteria of Eurocode 8 [12] can be exceeded for drifts significantly lower than the yield drift of the wide beam–column connections [1].

Another important conclusion from the literature is that problems of shear in wide beams can be successfully mitigated by the provision of shear reinforcement [13]. Moreover, the performance of the connections is improved when denser hoops are provided in the vicinity of the joints and when hoops are placed inside the joint [14,15].

Typical cracking patterns due to reversed lateral loading are presented in Figure 4, based on [10,16,17]. Flexural cracks can develop in the beam. Depending on the amount of reinforcement and cross section, flexural cracks can also form in the column. Inclined flexural cracks originating from the corners of the columns are also observed in some experiments, especially when the ratio between beam width and column width is high, resembling flat slab–column connections. When the width of the beam is greater than that of the column, torsional cracks can develop in the transverse beam (Figure 4). Shear and joint shear cracks can also develop.

Especially in exterior beam–column connections, detailing of the transverse beam is very important in preventing torsional cracking and loss of lateral load capacity [18]. In Albania, spatial frames are normally used, with beams in two orthogonal directions. Nonetheless, there is a congestion of shear reinforcement in the vicinity of the column at the intersection of the orthogonal beams (Figures 2a and 5), making it difficult to execute properly and potentially leading to issues during an earthquake.

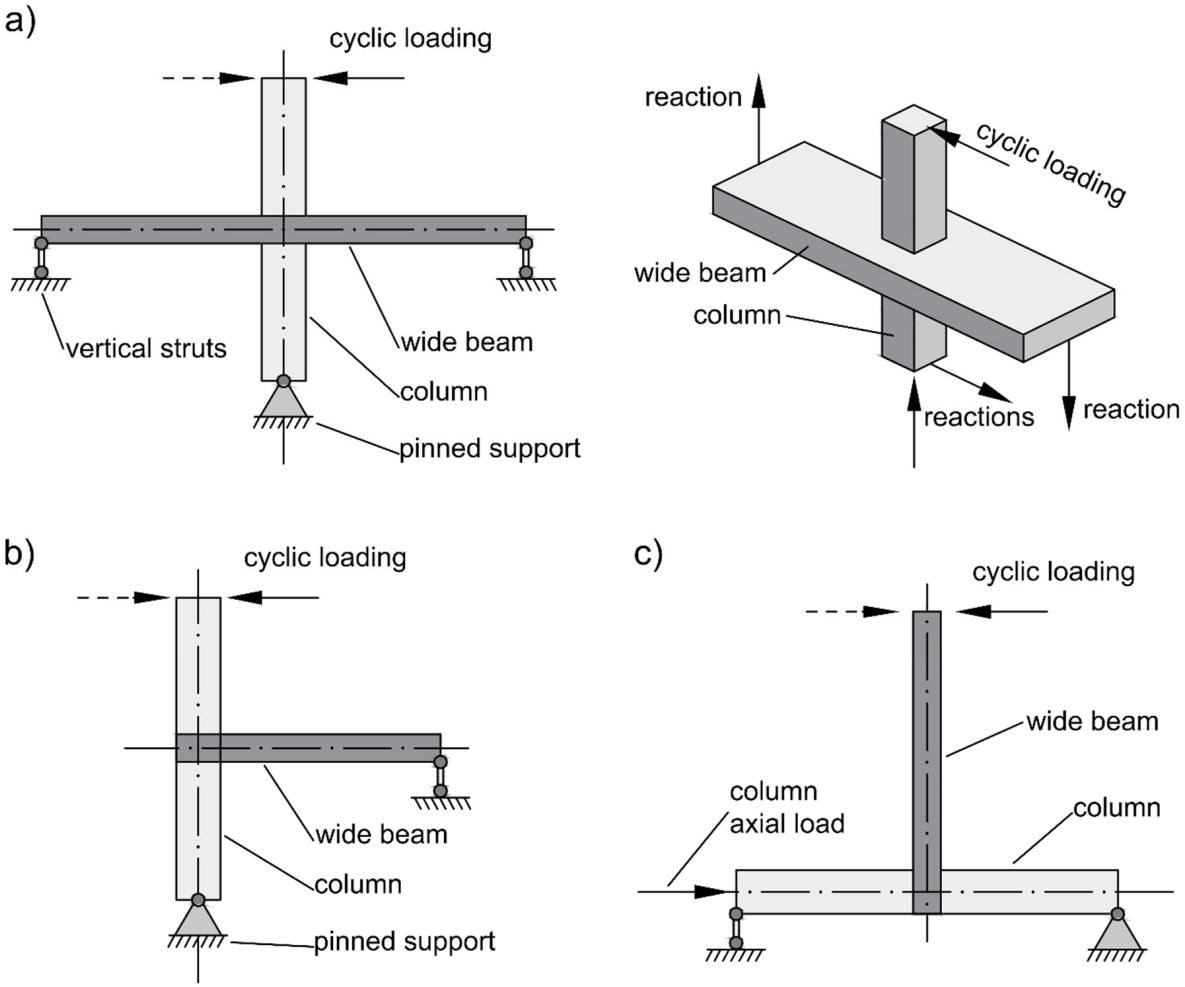


Figure 3. Typical test setups used in experimental campaigns found in the literature: (**a**) interior connections; (**b**,**c**) exterior connections.

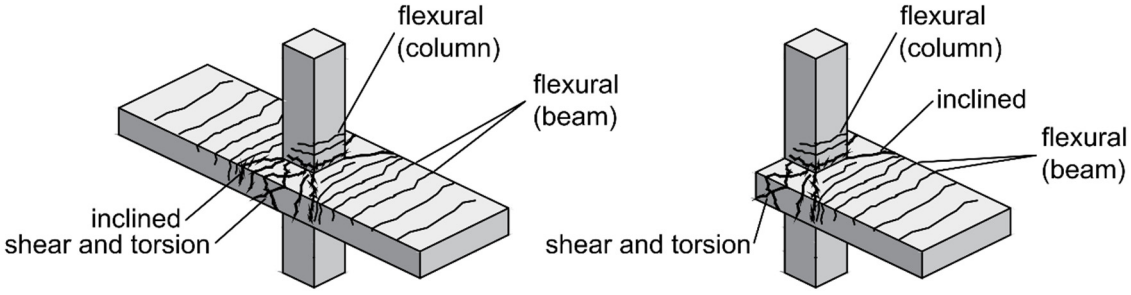


Figure 4. Typical cracking patterns in interior and exterior wide beam–column connections observed during experiments.

In review of the available experiments, it is noticed that beams with cross section dimensions comparable with those typical for RC structures in Albania (Figure 1) have already been tested. Few results from experiments of wide beams including a portion of the slab are available [13,19–21]. These experiments indicate that the slab participates more than it does in the case of deeper beams, resembling flat-slab systems with punching shear reinforcement. Referring specifically to flat slabs with punching shear reinforcement, [22] showed that such flat-slab frames can be designed to sustain relatively high levels of seismic demand without collapse, but damage limitation criteria can be violated for low seismic spectral accelerations and second order effects can play a significant role. The performance

in a post-earthquake scenario was discussed in [23], where it was shown that reloading after a major earthquake is associated with reduced stiffness and load (further accentuating issues related to the inherent flexibility). The load capacity is recuperated if proper detailing is provided to avoid brittle failures.

Figure 5. Congestion of reinforcement near the beam–column joint in a building in Durrës.

Waffle slabs with solid strips resembling wide beams discussed above are also used in some countries in the Mediterranean region (especially Italy, Spain and Portugal). Tests on waffle-slab systems [24,25] show that the behavior of these floor systems is similar to that of the other alternatives discussed earlier in terms of lateral stiffness.

It is worth noting that the study [26] highlights the significance of the rigid diaphragm in waffle slabs. When appropriately designed and executed, these slabs can function effectively as a rigid diaphragm in situations where spans are less than 6 m.

3. Observations from Past Earthquakes

The information regarding the seismic behavior of wide beams during major earthquakes is rather limited. Two main factors might have contributed to this scarcity of data. First, wide beams are used only in certain regions of the world. In other regions of the world, other alternatives such as flat slabs are more popular when flat soffits are needed. Secondly, the inspection of wide beams is generally difficult due to floor layers on top and suspended ceilings below that often conceal the beams. Nonetheless, information from past earthquakes in Turkey and Spain was found. These are two countries in which wide beams are popular.

In Turkey, embedded wide beams with joists and voids filled with lightweight clay blocks (called "*asmolen*") have gained popularity as slab systems [3]. In buildings up to six stories, buildings employing this slab system are often built without shear walls, whereas shear walls are typically provided in buildings with more stories [3]. In the Marmara region in Turkey, embedded beams are often used in the first floors of the building to increase the clear height whereas regular beams are used in the upper floors [27]. Nonetheless, the number of RC buildings with conventional beams remains higher than that with embedded beams in Turkey [3]. A large number of buildings with wide beams have been subjected to strong earthquakes over the years in Turkey. During the 1999 Kocaeli M_W7.4 earthquake, buildings with wide beam–column frames suffered widespread damage [28]. Cases of severely damaged or collapsed buildings of this typology have been reported and a detailed review can be found in [3]. In general, causes of collapse include poor detailing, structural irregularities and low quality of materials, which make it difficult to isolate the role of wide beams in the collapse and damage of these buildings [3]. In contrast to the Albanian seismic

design code [4] and Eurocode 8 [12], the Turkish seismic design codes contain explicit rules determining when wide beam–column frames are permitted [3,28], although these rules have been changing over time [3].

Wide beams are widespread in Spain [1,29,30]. In Lorca, Spain, the wide beams and the slab are often relatively thick due to the stringent deformation criteria in the local design code, but the columns have small sizes and shear walls are rarely used [31]. In the 2011 Lorca Earthquake, structural damage was mainly limited to ground floor columns failure in shear–axial failure mode and failure of captive columns. One building with waffle flat slab collapsed due to failure of the columns, with no significant signs of damage to the waffle flat slab [31]. Non-structural damage was widespread. A significant influence of non-structural infill and partition walls in the structural response of buildings was observed in the Lorca Earthquake [31].

Although evidence on the seismic behavior of wide beams after earthquakes is limited, there are several publications describing the performance of flat slab buildings during major earthquakes. For instance, the poor behavior of flat slab buildings was evident during the 19 September 2017, Mexico City earthquake [32]. Poor behavior has also been reported in earlier earthquakes in USA and Mexico [2,33]. In contrast, relatively good behavior has been observed during several major earthquakes in Greece [2]. As described in Section 2, flat slabs are similar to wide beam–ribbed slabs in terms of their lateral stiffness and energy dissipation capacity. However, it is necessary to note that flat slabs are susceptible to punching shear failure under lateral loading, as they are often non-shear-reinforced (especially in older structures). In this context, it is necessary to distinguish brittle shear failure from flexurally governed behavior in wide beams and flat slabs in post-earthquake studies. Wide beams typically used in Albania (Figures 1 and 2), in contrast to flat slabs without punching shear reinforcement, are usually heavily reinforced against shear, and shear failures are not expected to be the governing failure mode in most cases.

4. Observations from 26 November 2019, Albania Earthquake

Many reinforced concrete buildings in Albania suffered damage due to the M_w6.4 26 November 2019 earthquake and the subsequent aftershocks. The most common damage pattern was non-structural damage to partition and infill walls, but structural damage was also observed, mainly on columns, including several structural collapses and severely damaged buildings that were later demolished. Detailed descriptions of the earthquake and the associated damages are presented elsewhere [34–37]. The following paragraphs focus on wide beams and other observations related to them.

Data from reports and publications of other authors [34–37] as well as data gathered subsequently by the authors of this paper indicate that damage to wide beams was generally limited. Light spalling and minor cracking was observed in some cases. Such damage is presented in Figure 6, corresponding to a twelve-story building in Durrës. The building has three structurally independent blocks separated by relatively small seismic gaps. The structural system consists of a few shear walls and wide beam–column frames covering the majority of the floor area. The damage related to wide beams consisted in cracks running along the wide beam and minor crushing of concrete at the column end and the bottom surface of the beam (Figure 6). It is likely that these longitudinal cracks occurred at the interface between the wide beams and polystyrene blocks and joists. Minor flexural cracks were observed at column end sections. Besides issues in vicinity of the wide beam–column connections, this building suffered excessive damage to infills and diagonal cracking at the shear walls.

In another similar twelve-story building in Durrës (Figure 7a,b), shear cracks were observed in the exterior wide beams on the ground floor. This is a rare case in which significant structural damage was observed to the beams. The structural system of this building consisted of wide beam–large column frames covering the majority of the floor area (more details can be found in [38]). The damage related to wide beams consisted of large deflection and shear cracks in critical regions concentrated on the ground floor and

similar minor cracks in upper floors. Besides issues related to the local shear cracks in exterior beams in vicinity of the wide beam–column connections, this building suffered excessive non-structural damage in the first five floors (Figure 7c).

(**a**) (**b**)

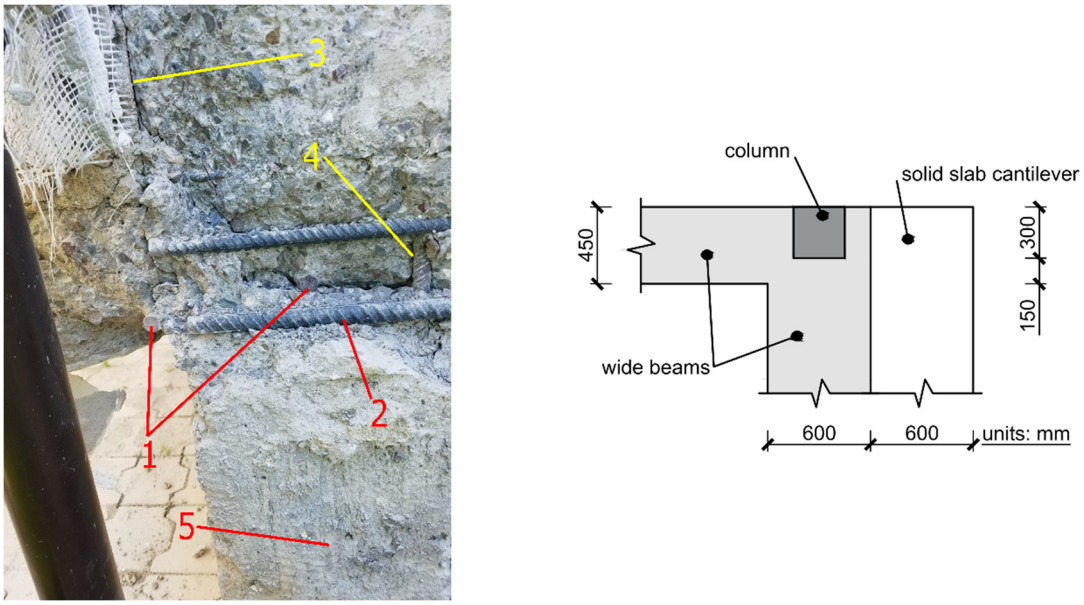
Figure 6. Damage in vicinity of wide beams in a twelve-story building in Durrës: (**a**) cracking on the bottom surface and damaged infills; (**b**) cracks on the bottom surface.

(**a**) (**b**) (**c**)

Figure 7. (**a**,**b**) Shear cracks in exterior wide beams at the ground floor; (**c**) building after removal of damaged non-structural elements in a twelve-story building in Durrës.

Insufficient anchorage of wide-beam longitudinal bars was detected in a four-story building in Tirana, resulting in the damage to corner beam–column connections, as shown

in Figure 8a. The figure shows that anchorage was sought to be achieved through straight bars (No. 1 and 2 in Figure 8a) that were anchored outside the column core (note the column bars No. 4 in Figure 8a and the column denoted by No. 5 in the figure). The crack denoted by No. 3 in Figure 8a is non-structural, corresponding to floor layers and the infill wall above the beam, but damage is also observed in the cantilevered part of the beam under the crack No. 3. The structural system of the building consisted of wide beam–column frames, without shear walls. A plan drawing of the damaged beam–column connection is shown in Figure 8b.



(**a**) (**b**)

Figure 8. Insufficient anchorage of beam bars in a corner beam–column connection: (**a**) observed damage; (**b**) plan drawing of the connection (note: 1, 2—straight bars used for anchorage, 3—a crack, 4—column bars, 5—the column).

Although damage to wide beams was rather limited in other buildings, these beams might have contributed to other damage patterns observed during the 26 November 2019 earthquake. For instance, the high flexibility of wide beams might have contributed to the excessive non-structural damage that was widespread after the earthquake. Both buildings described earlier in this section sustained significant damage to infill and partition walls. As mentioned earlier, the first building in Durrës (Figure 6) had few shear walls, whereas the second building in Durrës (Figure 7) and the building in Tirana (Figure 8) had no shear walls at all and the wide beam–column frames served as the only lateral load resisting system. The lack of shear walls, the insufficient amount of shear walls or the inappropriate placement of these walls in the floor layout was a common observation amongst damaged reinforced concrete buildings, especially in Durrës [34,35,37,38]. Under these conditions, the well-known high flexibility of wide beam–column frames (see Section 2) makes it difficult to control inter-story drifts during seismic shaking.

Examples of buildings with wide beams that suffered significant non-structural damage are given in Figure 9. In the building with wide beam–column frames shown in Figure 9a, damage was excessive, with in-plane and out-of-plane failures of the infill and partition walls. The building in Figure 9b also suffered damage to infills up to the fifth floor. Due to failure of the brick walls, it is possible to see in Figure 9b the exposed, apparently undamaged, exterior wide beam–column connections. The building shown in Figure 9c had an open ground floor (with very few infills compared to the upper stories). The structural system consisted mainly of wide beam–column frames, although a shear wall with small dimensions compared to the floor area was provided. Excessive damage to infills occurred

in this building in the lower five stories. Moreso, the building shown in Figure 9d had an open ground floor and suffered light-to-moderate structural damage on the ground floor and extensive non-structural damage on the first floor (infill and partition walls fell down). Only light damage occurred to the upper floors.

Figure 9. Examples of buildings with wide beams that suffered significant non-structural damage during the 26 November 2019, earthquake: (**a**) a twelve-story building in Durrës city; (**b**,**d**) a six-story building in Durrës seaside; and (**c**) a ten-story building with open ground floor in Durrës beach area (photo: Rikard Luka).

In fewer cases, column failure was observed whereas the beams remained almost intact. One example is given in Figure 10. Although the wide beams can easily adhere to the "strong column–weak beam" philosophy (as demonstrated also in [8]), such failures can occur due to improper detailing of the columns or the formation of soft-story mechanisms or short columns, as a result of the stiffening effect of masonry infill walls. The building in which the failures of Figure 10 occurred has five stories and wide beam–column frames

with no shear walls. The role of wide beams in the structural failure of the columns cannot be isolated in this building due to other issues such as poor detailing of longitudinal and transverse reinforcement (Figure 10a shows that insufficient hoops were provided and their detailing was inadequate, leading to opening of the hoops) and strong interaction with infill walls (Figure 10a,b). It can be stated, however, that low lateral stiffness in general helps the promotion of these types of failures, because the incompatibility between infill walls and the reinforced concrete structure becomes more apparent when the structure is flexible. Furthermore, second-order effects can play a significant role with the increase in horizontal displacements. Measurements on site indicate that there was a torsional rotation of the building and a nearly 7 cm residual drift was measured in the first story. The upper stories remained almost intact, indicating the formation of a soft-story mechanism and potentially a stiffening effect of the infill walls in the upper floors.

(**a**) (**b**)

Figure 10. Severely damaged columns with little-to-no damage in beams in a five-story building with wide beam–column frames and no shear walls: (**a**) opening of the hoops and interaction with infills; (**b**) shear failure and interaction with infill walls.

Another building, in which the influence of wide beams in the global response is easier to identify, is shown in Figure 11. This building was unfinished (Figure 11a), and the ground floor was open, with very few infill walls constructed at the time of the earthquake. In this building, no significant signs of distress were detected in the wide beams, but the column bases suffered damage which was mainly expressed by concrete crushing (Figure 11b). This response (i.e., with essentially elastic and undamaged beams and damaged column bases) is likely a result of the excessive flexibility of wide beams and the elevated value of yield drift for these beams. This issue is discussed in more detail in the following Section 5.

Table 1 presents a summary of the observed damage in RC buildings with joist and wide-beam floors during the 26 November 2019 Albania earthquake and are grouped according to damage pattern and severity. Although it is difficult to pinpoint the role of the wide beams in the cases of collapse and in some cases of heavy damage, the high flexibility of the wide beam–column connections likely contributed to the various damage patterns summarized in Table 1.

(**a**) (**b**)

Figure 11. Seven story building in Durrës: (**a**) building view; (**b**) damaged column bases.

Table 1. Damage patterns on RC buildings with joist and wide-beam floors: (1) Mechanism or damage pattern; (2) buildings features; (3) factors causing/contributing to damage; (4) examples from the Durrës area.

	Mechanism or Damage Pattern	Buildings Features	Factors Contributing to Damage	Examples from the Durrës Area
Collapse	Soft storey and/or pancake	Low/mid-rise flexible structures; Higher and open ground floor; Many of them constructed without permit or violating it; few or none seismic criteria followed in design and/or construction; Housing sector.	Lack of seismic capacity; insufficient column dimensions; low concrete strength; low percentage of reinforcement and lack of seismic details, especially for shear capacity; infills columns interaction; added floors;	
Heavily damaged	Extensive structural damages or near-collapse, concentrated at the top of the columns of the ground floor	Low/mid-rise flexible structures; usually with higher and open ground floors; grater mass (cantilever area) and stiffness (masonry infills) in the upper floors. Mostly part of tourism sector.	Lack of adequate resistance and ductility; low concrete strength and often poor seismic details, especially for shear capacity; infills-columns interaction; added floors; site amplification effect	
Moderate damage	Minor-to-moderate structural damages and extensive non-structural damages	Mid/high-rise flexible structures (including those with torsional flexibility); usually with higher and open ground and first floor. Mostly part of housing sector	Lack of or not properly placed shear walls; high irregularity; poor connection of infill and simple walls; insufficient shear capacity; inadequate seismic joints; seismic site amplification effect	

5. Analysis of the Role of Wide Beams in the Overall Seismic Behavior of RC Buildings

5.1. A Case-Study Building in Durrës

A four-story RC building located in Durrës is analyzed in this section. The building is representative of older (around 1990–2000) RC buildings in Albania, in which wide-shallow beams were used in combination with relatively thin columns. This building typology continues to be widespread in suburban areas near Durrës (Figure 12) and it was one of the most severely affected by the November 2019 earthquake.

Figure 12. RC Buildings with wide beams and an open ground floor.

A general description and main structural properties of the building can be found elsewhere [38].

The analyzed building is mid-rise (four-stories high), located in an area characterized by weak soil deposits, and has an RC frame system with 4.5 m maximum span and RC columns 30 × 30 cm. The floor system is a cast-in-place RC slab with shallow beams (depth 20 cm, equal to the slab thickness). Masonry infill walls are present on the upper stories but are absent on the ground floor. Foundations are composed of footings connected with each other with tie beams.

Figure 13 gives various details of the structural plan of the building, as it was designed. The structural plan is given in Figure 13a, horizontal elements (slab and beams) are given, respectively, in Figure 13b,d and one of the columns is shown in Figure 13c.

A total of six plane frame finite-element models were built in the software package SeismoStruct [39]. One of the models represents a frame of the building in the longer direction based on the original design, which had a ground floor height of 4.1 m (as opposed to 3.15 m for the upper two floors and 2.9 m for the top floor) and a reduction in the size of the columns in the upper two stories (from 30 cm × 30 cm to 25 cm × 25 cm). In the following, this model is referred to as model "Original" (i.e., following the original design). Another model, called "Original-regular", was identical to "Original", but had a ground floor height of 3.15 m, making it regular in elevation. The two other models, one irregular in elevation and the other regular, were built with columns sized 30 cm × 30 cm and were uniform along the height. This was in fact observed during site visits, and it represents the actual state of the building. These two models are called "AsBuilt" and "AsBuilt-regular", respectively. Finally, two other models were built with a hypothetical column size of 50 cm × 50 cm and a longitudinal reinforcement ratio of 1.5%. The two models with bigger columns were named "StrongCol" and "StrongCol-regular" (again, the latter had uniform story heights of 3.15 m). The two models with stronger columns are representative of more recent buildings in Durrës and Albania in general. The models are illustrated and further described in Figure 14.

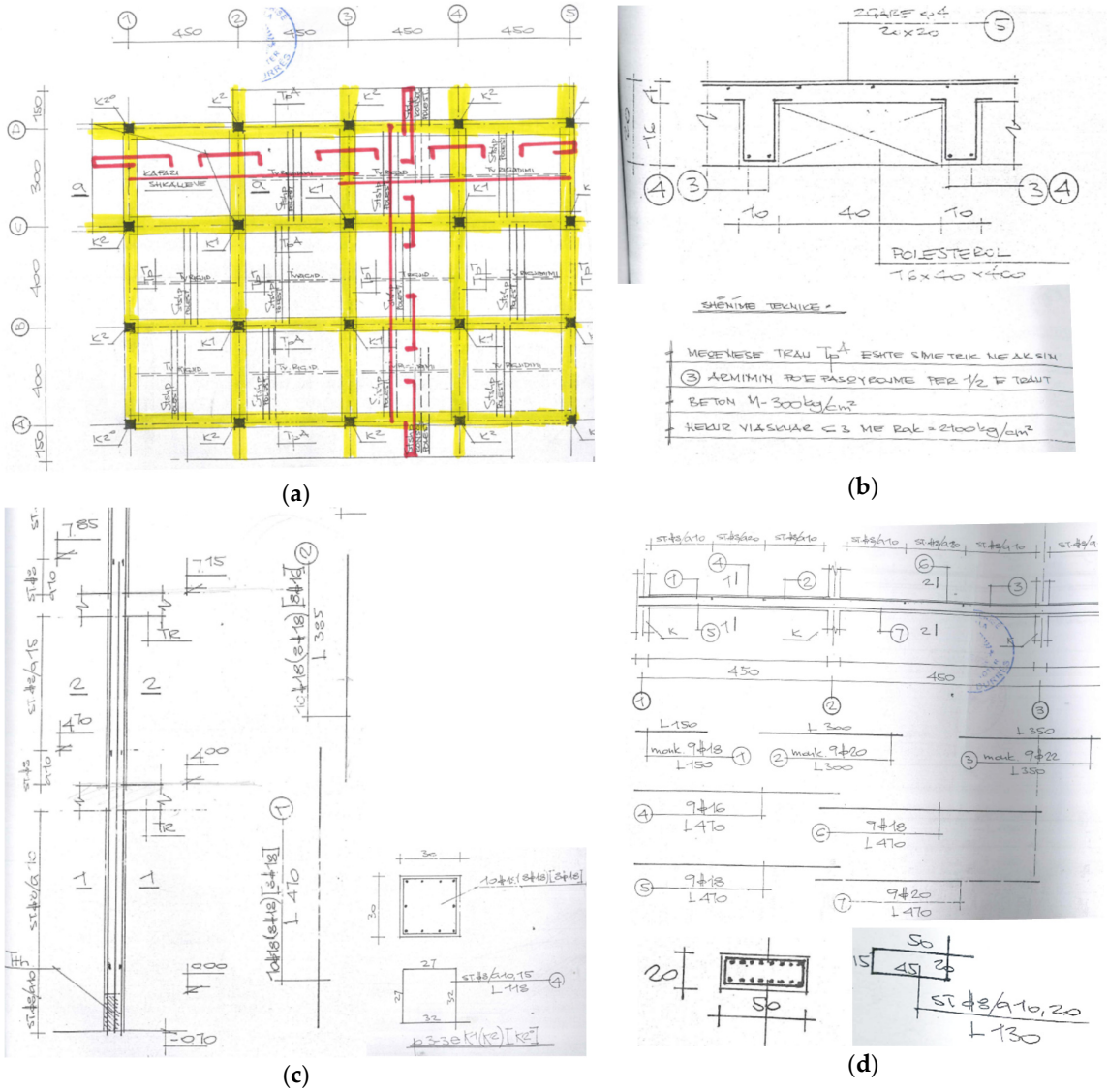


Figure 13. Structural design of the building: (**a**) structural plan; (**b**) two-way waffle/joisted slab system and technical notes; (**c**) column dimensions and reinforcement; (**d**) beam dimensions and reinforcement.

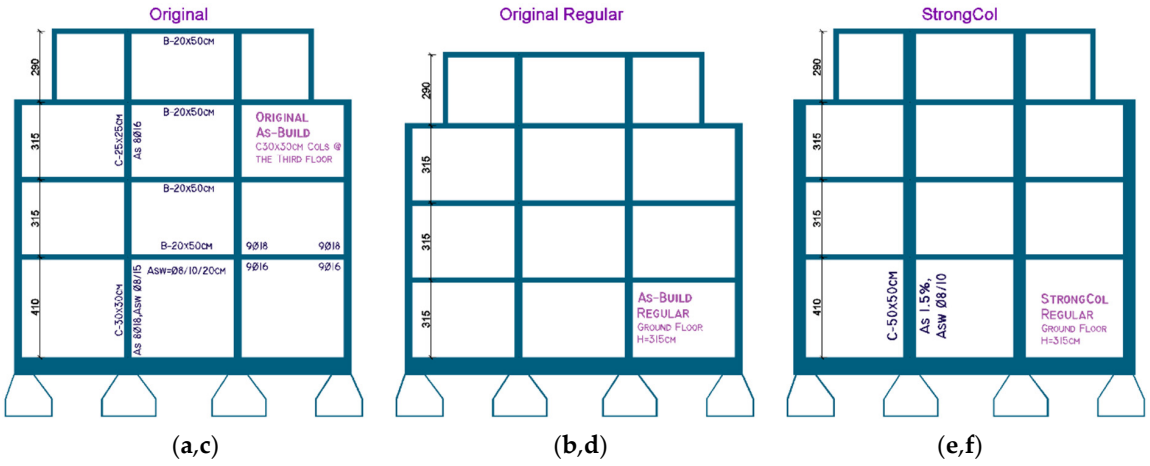


Figure 14. Numerical models: (**a**) Original; (**b**) Original-regular; (**c**) AsBuilt; (**d**) AsBuilt-regular; (**e**) StrongCol; (**f**) StrongCol-regular.

Plane models were considered for simplicity, but a pushover analysis applied to a 3D model resulted in results consistent with what is discussed below.

Based on destructive (Table 2) and nondestructive tests performed for various building members, the columns and beams for all models were considered to have a concrete cylindrical compressive strength of 13 MPa and 16MPa, respectively. The yield strength of the rebars was taken as 500 MPa. The concrete compressive and rebar yield strengths given in the design specification (concrete cylinder compressive strength 25 MPa and steel yield strength 240 MPa), differ from the destructive and non-destructive test results.

Table 2. Destructive tests results for different building members.

Item	Concrete Core Diameter (cm)	Cylindrical Strength (MPa)
Column C-3 (1st Floor)	7	13.63
Column C-2 (1st Floor)	7	9.17
Column (1st Floor)	7	8.34
Column D-2 (Ground Floor)	5	13.8
Column D-5 (2nd Floor)	5	13
Beam 2-2, C-D (1st Floor)	5	30.3

The columns and beams were modelled as inelastic plastic hinge force-based frame elements with a fiber section. The nonlinear models were built with concentrated non-linearities (plastic hinges) at both extremities of each element (beams and columns). The capacity of plastic hinges was determined based on the element cross-section geometry, the bending and shear resistance of the sections as well as the amount and distribution of the longitudinal and transversal reinforcement. For material nonlinearity, the existing models available in the software package were used (Mander et al. model [40] for concrete and bilinear isotropic hardening model for reinforcement).

A triangular lateral load pattern was applied (with zero at the base of the building) and the roof displacement was monitored, resulting in the pushover curves shown in Figure 15. The failure mechanisms are shown in Figure 16.

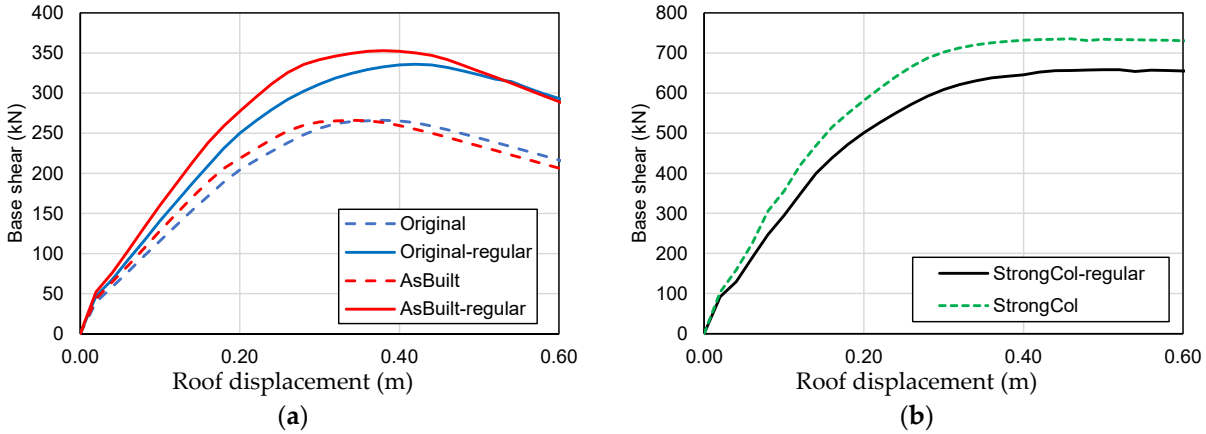


Figure 15. Pushover curves for the frames under consideration: (**a**) models with weak columns; (**b**) models with strong columns.

Figures 15 and 16 indicate that all the models with weak columns have a failure mode in the form of a soft story at the ground floor or at the second floor in the case of model "Original-regular". This result is consistent with observations on site in this building and many buildings of a similar typology in the earthquake-affected area.

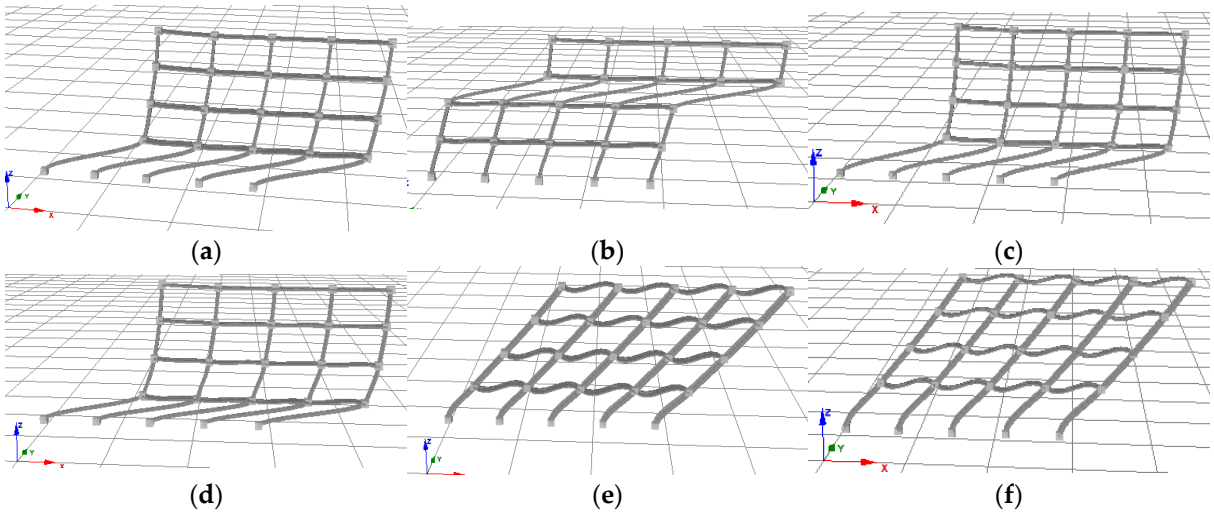


Figure 16. Deformed shapes at failure of the models: (**a**) Original; (**b**) Original-regular; (**c**) AsBuilt; (**d**) AsBuilt-regular; (**e**) StrongCol; (**f**) StrongCol-regular.

Furthermore, both the "original" and the "AsBuild" model evidently show the difference in pushover curve capacity between the existing "irregular" models and their corresponding "regular" (Figure 15a) in elevation model. The model "irregular" in elevation has a reduced capacity in strength by 20–25% and a reduced capacity in displacement by 15–20%.

Even though these buildings had flexible wide beams, the columns were very weak and the soft-story mechanism developed in the numerical model, even when the building was regular in elevation (for example in case of model AsBuilt-regular). Note also that the models above had no infill walls, but it can be deduced that the formation of the soft-story mechanism is further aided by the presence of infill walls in the upper stories and the lack of them on the ground floor, which is typical for suburban buildings in Albania.

As expected, the building models with stronger columns (StrongCol and StrongCol-regular) were able to develop a strong column–weak beam mechanism and much more ductile behavior compared to the other models shown in Figure 15a. In fact, the columns in these two models can still be considered rather small in size—only 50 cm by 50 cm. Furthermore, the strong column–weak beam mechanism was developed even in the model with higher ground floor (model StrongCol). Nonetheless, attention should be paid to the displacements in Figure 15b. Although it is true that the failure mechanism is a desirable and ductile one, the building models are rather flexible. This can be deduced by analyzing Figure 17, in which the inter-story drifts in model StrongCol are plotted as a function of the base shear. The vertical dotted line in Figure 17 represents a drift ratio of 0.5%, corresponding to the drift limit required in Eurocode 8 [12] for buildings that have brittle non-structural elements (such as the perforated brick walls commonly used in Albania). The vertical line intersects the curves in Figure 17 for a base shear approximately 200 kN, corresponding to a roof displacement of approximately 6 cm (see also Figure 15b) for the two upper stories. It is notable that the drift limit for damage limitation is attained very far (in terms of displacements and drifts) from the formation of the global yield mechanism and very close to the origin of the graphs for a global behavior that is still almost linear elastic. This behavior is consistent with the widespread damage to infills that was observed in relatively new RC buildings in Albania after the earthquake when they had no shear walls and only column–wide beam frames. In buildings with wide beam–column frames, the high lateral flexibility means that damage limitation criterion is easily violated, while the structure can remain intact and sustain much higher seismic demands.

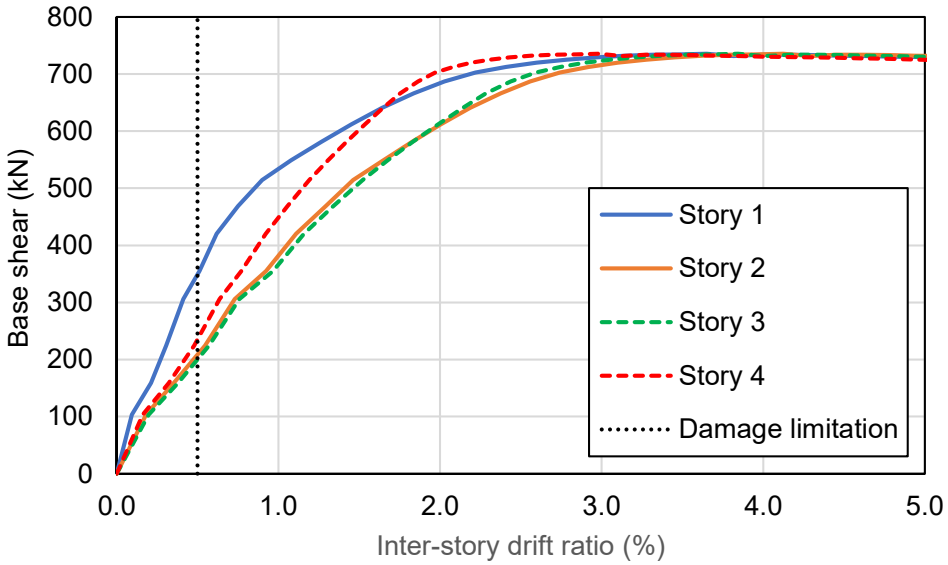


Figure 17. Inter-story drifts in model StrongCol.

Finally, based on the analysis described above, it should be acknowledged that wide beam–column frames such as those represented by the models "Original" and "AsBuilt" can be retrofitted rather easily by increasing the column sizes (for example by concrete jacketing) and this can lead to a significant improvement in terms of collapse prevention and the formation of ductile failure mechanisms. On the other hand, the analyses above showed that special attention is needed to mitigate serviceability and damage limitation issues, which can remain critical in these types of RC buildings even when the column sizes are increased.

5.2. Yield Drifts of Wide Beam–Column Assemblies Based on Experiments

In further support of the conclusions of the analysis presented in Section 5.1, and for a more general view of the response of wide beam–column frames typically used in practice, tests from the literature are analyzed. For this analysis, only interior beam–column connections are considered. Based on the literature review, however, it is important to state that exterior connections can suffer from severe issues such as torsional cracking and joint failure when not properly detailed (see Section 2). Moreso, only beam–column assemblies corresponding to ground floor or intermediate stories are considered in this analysis, although tests on roof-level connections exist [41].

The main properties of the specimens taken into account are summarized in Table 3, where b_b and h_b are beam dimensions (width and depth, respectively), b_c and h_c are column dimensions, with h_c being the dimension along which the lateral load acts. The table also contains the span length (L), reinforcement ratio of top beam reinforcement (ρ_t), reinforcement ratio of bottom beam reinforcement (ρ_b), the column's longitudinal reinforcement ratio (ρ_L), as well as concrete cylinder compression strength (f_c) and steel yield strength (f_y). For some specimens in Table 3, information about concrete cover was not found. In these cases, a concrete cover equal to 20 mm was assumed. The influence of this assumption on the discussions in this section is expected to be negligible. The test setup for all the specimens in Table 3 was similar to that illustrated in Figure 3a.

With respect to Table 3, it is worth noting that the tested specimens generally have short spans compared to common practice. This is further accentuated in specimens with large column dimension h_c (for example, specimen IWB1 from [6]), in which the clear span is relatively short. On the other hand, the beam depths of specimens in Table 3 are comparable with those commonly encountered in buildings, except for the specimens of [8], which are relatively thin. The experimental yield drifts resulting from Table 3 for the majority of the specimens are therefore expected to be lower than the yield drifts of wide

beams typical for reinforced concrete buildings (with generally larger spans but comparable beam depths).

Table 3. Main properties of beam–column interior connections from the literature.

Publication	ID	b_b (mm)	h_b (mm)	b_c (mm)	h_c (mm)	L (m)	ρ_t (%)	ρ_b (%)	ρ_L (%)	f_c (MPa)	f_y (MPa)
Quintero-Febres and Wight 2001 [13]	IWB1	889	305	356	356	4.52	0.5	0.4	2.7	36	462
	IWB2	660	305	356	356	4.52	0.7	0.6	2.7	28	462
	IWB3	838	305	330	508	4.52	0.7	0.6	1.9	26	455
Kulkarni and Li 2008 [6]	IWB1	800	300	300	900	3.76	1.4	1.0	2.5	64	460
	IWB2	800	300	900	300	3.16	1.4	1.0	2.5	66	460
	IWB3	800	300	300	900	3.76	1.4	1.0	2.5	48	460
Benavent-Climent et al., 2010 [8]	IL	480	180	270	270	2.95	2.4	1.4	Var *	25	404
	IU	360	180	210	210	2.95	2.3	0.8	Var *	25	404
Fadwa et al., 2014 [16]	IWBCC	900	300	400	450	3.60	0.8	0.5	2.1	29	495
Elsouri and Harajli 2015 [14]	IJ-F1	800	250	250	700	3.35	1.6	1.1	1.4	23	627
	IJ-F2	800	250	700	250	3.35	1.6	1.1	1.4	21	627
	UIJ-F1	800	250	250	700	3.35	1.4	0.9	1.4	40	566
	UIJ-F2	800	250	700	250	3.35	1.4	0.9	2.1	37	584

* different column section below and above the beam.

For all the specimens of Table 3, approximate moment (M) drift ratio (d_r) data extracted from the original publications are presented in Figure 18. The unbalanced moment is obtained as the lateral load multiplied by the lever arm, which is equal to the distance from the horizontal loading actuator to the bottom pinned connection to the floor (refer to Figure 3a). Bilinear elastic perfectly plastic approximations of the d_r–M curves are also plotted in Figure 18. The bilinearization is conducted on the basis of maintaining equal areas under the two curves up to the drift corresponding to the attainment of maximum moment M (as in Annex B of Eurocode 8 [12]).

The yield drifts obtained from the bilinear curves of Figure 18 are above 2.0% for the majority of the specimens. However, some outliers are present, with yield drift below 1.0%. For instance, specimen IJ-F1 suffered in shear, resulting in low capacity and low ductility [14]. The other outliers are the specimens IWB1, IWB2 and IWB3 tested by [6]. Likely contributors are the relatively short clear span, torsional cracking in the transverse beam and bond deterioration of the column rebars during the tests [6].

Likely contributors to the scatter of the results are the relatively short clear span, torsional cracking in the transverse beam and bond deterioration of the column rebars during some tests [6]. As already discussed earlier, the high yield drift of the wide-beam frame means that the wide beams are expected to remain almost elastic, even for rather severe shaking, unless premature brittle failures occur. On the other hand, column bases and shear walls (when they are present) are expected to yield much lower drifts. As a consequence, column base sections remain the only inelastic energy dissipation sources during an earthquake if shear walls are not provided. Moreso, the high flexibility means that damage limitation criteria are difficult to fulfil without shear walls or braces, in accordance with the analysis presented in the previous section (Section 5.1). Further experimental and/or numerical investigation is recommended.

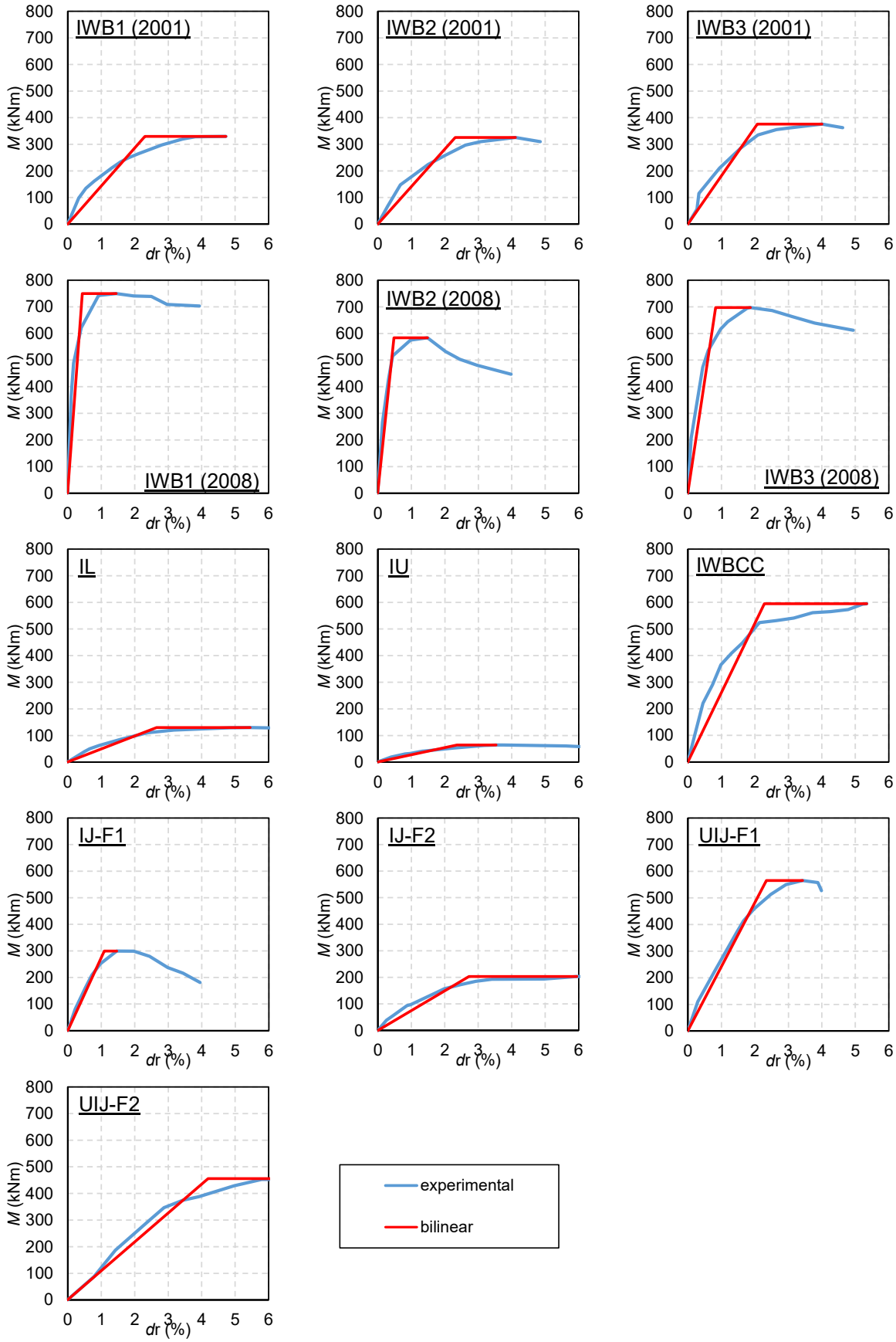


Figure 18. Experimental moment drift curves and bilinear approximation curves.

6. Conclusions

RC buildings of varying configurations, lateral load resisting systems and size were subjected to the strong 26 November 2019, Albania earthquake. Observations from site visits focused on the behavior of wide beam–column connections and findings from the literature were reviewed in this paper. The main conclusions are listed below.

1. In general, limited damage was observed in wide beam–column connections in Albania. Light cracking was observed in several buildings. In one building in particular, shear cracking of the beams was observed. On the other hand, damage to the columns in the visited buildings ranged from none to severe;
2. Experimental research on the seismic behavior of wide beam–column connections suggests that the lateral stiffness of wide beam–column connections is low, which is in agreement with the widespread non-structural damage observed in Durrës. For higher seismic demands, phenomena such as rebar slippage and torsional cracking have been reported during experiments. These phenomena were observed in very few cases during the limited field visits in Durrës, even in buildings that suffered severe structural damage to the vertical elements;
3. A large number of multi-story buildings suffered severe damage to masonry infill and partition walls. A likely contributor to this non-structural damage was the low lateral stiffness of wide beam–column frames;
4. Due to the structural characteristics of wide-beam frame buildings, especially those with irregularities in elevation, the nonlinear analyses showed that a soft-story mechanism can be triggered. This soft story mechanism was observed in several cases in Durrës;
5. With reference to the analyzed case study, the irregularity in elevation reduced the seismic capacity of the building by more or less 20%. It was shown that a "strong column–weak beam" hierarchy can be achieved rather easily with wide beams, but the inherent flexibility of the system can remain an issue;
6. Although beams with cross sections and detailing similar to that of beams typically used in Albania have been tested in the past, the literature review revealed that there is a lack of experimental data representative of span lengths in the range of 5–7 m typically encountered in practice. Therefore, further research is recommended.

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