Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 05, May, 2024

Upgrading of Precast Roof Beam–Column Connections with Seismic Safety Key Devices

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Received 03 February 2024; Revised 17 April 2024; Accepted 22 April 2024; Published 01 May 2024

Abstract

To meet the increasing demands for innovations in precast systems with high seismic resistance, in this study, we introduced a novel seismic upgrading technique for roof beam-column (RBC) connections, termed the targeted seismic upgrading (TSU) method, incorporating the innovative seismic safety key (SSK) devices we developed. These devices significantly enhance seismic resilience, offering a substantial improvement over traditional pin-based RBC connections in precast structures, which are known to have limited effectiveness. Our experimental tests on half-scale models of conventional RBC connections, coupled with comprehensive refined finite element method-based nonlinear analytical studies, conclusively demonstrated the enhanced seismic retrofitting capabilities of RBC connections augmented with SSK devices. The paper delineates a technical procedure for applying the SSK, our proprietary innovation, for the targeted seismic upgrading of RBC connections within modern precast systems. Notably, the SSK-upgraded RBC connections exhibited a marked increase in safety, as evidenced by results from experimentally validated nonlinear three-dimensional micro-analytical models. The incorporated flexible design elements in the TSU method ensure its high effectiveness and general applicability for seismic upgrading of both existing and new precast industrial hall structures, offering a significant advancement in this specific seismic engineering topic.

Keywords: Precast Structures; Connections; SSK Device; SSK-Upgraded Connections; Model Testing; Seismic Performance.

1. Introduction

Following the permanent intensifying construction of traditional precast industrial hall structures in seismic areas worldwide, the existing structural and connection problems have not been explored extensively. Furthermore, the observed short-term seismic losses and long-term secondary economic consequences have not been estimated quantitatively and qualitatively. The observed seismic losses of the precast structures following any strong earthquake occurring worldwide are commonly expressed as the induced intolerable heavy damages or total structural failures [1, 2]. However, following the assured improvement of technological possibilities, large-scale prefabricated elements have lately been produced and used. Accordingly, structural engineering related to prefabricated structures has experienced significant changes in the design and construction of these structures. Precast elements are being increasingly used in the construction of bridges, buildings, tunnels, and facilities for specific purposes. However, a particularly expressed and dominant progress is evident in the construction of industrial capacities, the most present among which are large-

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http://dx.doi.org/10.28991/CEJ-2024-010-05-06

scale, typified industrial halls. The purpose of the constructed industrial halls is diverse since they provide huge space by applying a relatively small number of precast elements. Prefabricated elements are most frequently designed, typically for different types of halls.

Construction companies usually have their own hall program, which includes single-bay, double-bay, triple-bay, and multi-bay halls along length, corresponding to the needs of the local markets. Along with height, industrial halls are most frequently built as single-story structures in the form of ground-floor structures. However, in many cases, prefabricated industrial halls are also built as two-story, three-story, and multi-story structures. Although prefabricated industrial halls belong to the group of high-rise structures, the existing regulations on high-rises do not hold for them due to their story heights, extraordinarily large spans, and specific distribution of present weights (masses). The industrialization of all regions worldwide has abruptly increased the presence of industrial halls in seismic regions. In seismically active regions in North, Central, and South America, industrial halls are mass-constructed using precast or semi-precast structural elements. Moreover, in all Asian countries like China, Japan, Indonesia, India, and other countries located in seismically active areas, the construction of precast or semi-precast industrial halls has increased abruptly. The situation is similar in Europe, and almost in all countries situated in the seismic zones of Southeast Europe, such as Italy, Greece, Turkey, all Balkan countries, and others, the construction of precast industrial halls is being increasingly intensified.

The precast industrial halls are increasingly built using traditional or locally developed construction technology. Due to insufficient knowledge on the dynamic behavior of industrial halls under the effect of strong earthquakes, extremely high and insufficiently controlled seismic risk has been generated abruptly. The competent state authorities most frequently have insufficient information on observed problems because each earthquake that occurs inflicts certain uncontrollable and intolerable damage and consequences. In almost all cases of the latest strong earthquakes in the region and worldwide, the heavy consequences expressed by failure or damage to industrial halls have usually been unreasonably justified by the so-called “effects of a surprise.” In many cases, during the failure of industrial halls, integral factory machines and equipment that may be 10–20 times more expensive than the industrial hall structure are completely destroyed. Considering the huge consequences that occur in the case of heavy damage or total failure of industrial halls, presently, a global realistic need remains for investigating the actual seismic performances of these specific structures to determine improved innovative solutions that will not only incur a considerable rise in the price of these structures but also contribute to multiple decreases in the seismic risk. Commonly, many recent earthquakes have demonstrated that the majority of existing precast structures possess poor seismic resistance, even those located in seismically very-active regions in Europe and elsewhere worldwide. Intensified research has recently been conducted, and case studies exploring methods to mitigate the extremely high seismic risk associated with the presence of such structures have been accomplished.

Historically, precast structures, particularly those designed without seismic considerations, have poorly performed in earthquakes. Precast industrial structures are often highly vulnerable to seismic events, even in the most developed countries. A high vulnerability of precast structures was observed in Northern Italy, where the 1976 Friuli earthquake [1, 2] and the 2012 Emilia earthquake [3] had severe economic impacts. The observed damage and collapse of precast industrial buildings, specifically following the 2012 Emilia earthquakes, have been systematically reviewed [4, 5]. Similarly, building failure patterns and the shortcomings of the Turkish Earthquake Code were detailed in the context of Turkey [6, 7]. A special report on lessons learned from recent catastrophic events emphasized the essential need to improve the seismic safety of precast structures [8]. Comparable conclusions were drawn from field observations after the Lorca earthquake in Spain on May 11, 2011 [9]. Regarding the research activities conducted over a period of more than half a century, significant advancements have been made in construction technologies for precast systems. An early milestone in the systematic development of advanced building technologies under the seismic conditions of the Balkan region was the publication of a normative book related to the design and construction of prefabricated RC building systems [10]. A significant contribution to the construction of precast concrete buildings was also made by the inaugural Fédération Internationale du béton (FIB) publication [11]. In recent years, experimental studies have addressed many specific technical challenges, including seismic tests on a full-scale three-story precast concrete building [12] and examinations of the seismic performance of mechanical connections [13].

Additional studies include cyclic nonlinear behavior testing of dowel connections [14], experimental tests of “pinned” beam-to-column connections [15], and the influence of cladding on the seismic response of precast structures [16]. Analytical studies have contributed substantially to the field, including seismic assessments of existing precast industrial buildings [17, 18] and analyses of the failure and cyclic capacity of beam-to-column dowel connections [19–22]. Innovative studies have also made significant strides, such as seismic vulnerability assessments of precast RC structures [23], the development of a new passive control technique for precast frames [24], and the introduction of self-centering precast concrete frame connections [25, 26].

Regarding a long period of approximately 50 years, the various design errors of prefabricated elements or connections were clearly identified as frequent and common sources for damage or failure of precast industrial structures under their life-time loading [27]. To upgrade the construction systems of precast structures, the novel geometries and connections allowing robotic manufacturing have been studied and discussed. Due to the complex structure of the created joints, their installation in many cases can be relatively difficult. To minimize waste production, the respective procedures for the construction of prefabricated components using waste materials were studied. To improve the performance of precast concrete joints, a specific study for the application of high-strength fiber-reinforced concrete was conducted [28–31]. Significant upgrading of connections in precast buildings can reportedly be achieved with modifications to the implemented joint materials [32]. The authors recently accomplished an extensive study for the development of an innovative, modern, and seismically safe precast system, which is applicable in regions characterized by pronounced-to-high seismicity. The obtained results from the conducted experimental laboratory tests of models and analytical investigations provided qualitatively advanced original knowledge, contributing to a deep understanding of the critical safety aspects of the integral precast industrial hall structures [33]. Currently, the development of seismically safe systems has become a highly important issue since these structures frequently house special industrial equipment whose value multiply exceeds the value of the integral structures. The importance of the study topic was discussed above based on published literature showing the observed severe damage effects on these types of structures during past earthquakes. Important results were obtained from our extended experimental and analytical study.

Our experimental study involved the realization of six specific quasi-static tests of constructed large-scale physical models of critical structural connections, including:

- Testing of a constructed model representing the connection between a precast RC column and a precast RC footing and processing of the original experimental results, model M1.
- Testing of a constructed model representing a prefabricated joint between an RC column and an RC corbel (short cantilever) and processing of the original experimental results, model M2.
- Testing of a constructed model representing the original connection between a precast longitudinal RC beam and an RC column and processing of the original experimental results, model M3a.
- Testing of a constructed model representing the improved original connection between a precast longitudinal RC beam and an RC column and processing of the original experimental results, model M3b.
- Testing of a constructed model representing the original connection between a precast roof RC beam and an RC column and processing of the original experimental results, model M4a.
- Testing of a constructed model representing the improved original connection between a precast roof RC beam and an RC column and processing of the original experimental results, model M4b.

The experimental results were of great importance for determining the main controlling parameters of the real nonlinear behavior of the tested individual connections and components, as well as the realization of the analytical investigations, including refined theoretical modeling of the tested connections and analysis of the nonlinear seismic performances of the integral structural systems under simulated strong real earthquakes.

The extended research comprised the realization of the combined analytical and experimental study, including:

- Study of seismic performances of the common precast prototype. The formulated refined nonlinear analytical model, involving realistic modeling of the existing common connections, has shown pure structural safety in the case of simulated real strong earthquakes.
- Analysis of the seismic safety of the upgraded precast prototype. The analytical study conducted with modeling of the tested upgraded connections has demonstrated improved structural safety. However, to assure structural safety under the strongest seismic actions, the need for qualitative upgrading of the existing connections was clearly confirmed.
- Creation, testing, and modeling of the adaptive innovative seismic safety key (SSK) devices applicable for rapid technological advancement of the existing and new critical connections were accomplished and described in this paper.

The concept of the present research was created following our accumulated experience in the field, including direct field damage inspections, laboratory testing of various physical models, refined nonlinear behavior modeling, seismic response simulation applying advanced analysis methods, and the creation of technological innovations. Our main aim was to conduct a wider integrated study focused on the development of novel engineering methods, tools, and measures assuring adaptive structural seismic upgrading and efficient elimination of the observed intolerable damages to precast structures. Focusing the present research on efficient upgradation of the highly vulnerable roof beam-column (RBC) connection, the importance and novelty of the conducted research are evident. The related sub-project was realized considering the following four interactive research pillars:

- ***Existing research gap:*** Under strong earthquakes, the original RBC connections are exposed to severe damage and failure. The heavy destruction of RBC connections under strong earthquakes was directly confirmed with our extensive field damage inspections, laboratory testing of the constructed prototype model M4a, and advanced seismic response simulation studies. The constructed and tested classically upgraded original RBC connections were also exposed to failure due to the limited upgrading effect achieved with the classical upgrading method. The poor upgrading effect was clearly confirmed with the experimentally tested model M4b. An extended, detailed review of the published literature confirmed that a more efficient upgrading solution does not exist. The present innovative and specifically targeted research was conducted to fill the existing research gap.

- ***Multi-focal research flow:*** To optimally fill the research gap, specific multi-phase research and development study was conducted, including: (1) testing of constructed prototype model M4a, representing the original RBC connection; (2) testing of constructed prototype model M4b, representing the upgraded original RBC connection; (3) creation of novel SSK-1 and SSK-2 upgrading devices; (3) testing and modeling of SSK-1 and SSK-2 devices; (4) confirming the high safety level of upgraded RBC connection with novel SSK devices, based on implemented advanced refined micro-modeling concept; (5) confirming of the high safety level of integral precast structure having upgraded RBC connections with novel SSK devices, based on implemented advanced tridimensional nonlinear analytical model.

- ***Novel upgrading method:*** The analytically modeled precast structure with classically upgraded RBC connections showed an unsafe response under extremely strong earthquakes. However, structural safety under the strongest seismic actions, PGA = 0.7 g, was assured with the implemented advanced upgrading of the existing RBC connections using the developed SSK-based upgrading devices.

- ***Step of upgrading design provisions:*** To extend the availability of the idea of targeted upgrading of RBC connections when they are possibly exposed to very strong earthquakes, application of the developed SSK-based upgrading method was proposed as the respective tool for advancing the design provisions.

This paper introduces the advanced, non-traditional targeted seismic upgrading (TSU) method for upgrading RBC connections in a modern precast N system, employing specially developed SSKs. This method was developed in response to the need for innovative solutions since we have confirmed with experimental tests that the classical upgrading technique is not applicable for effective upgrading of RBC connections. The efficiency of the TSU method was demonstrated through results obtained from experimental tests on large-scale prototype models representing both the original and an upgraded roof beam-column (ORBC and URBC, respectively) connections [27–29]. This innovative study is part of a broader project supported by PUT Inženjering, Niš, Serbia, dedicated to laboratory testing of prototype models of various connections of widely used precast N systems.

2. Study Objectives and Methodology

The N precast system is predominantly employed in the construction of expansive industrial hall structures, typically enveloping areas of 20,000 m² or more. Such vast dimensions are achieved through the implementation of successive, extensive spans between columns along the structure’s x-axis and a larger number of smaller spans along the y-axis. The integral roof-bearing RC structure, consisting of primary and secondary RC girders in conjunction with other roof components, is considerably massive, thereby inducing significant seismic forces during intense earthquakes. The often excessively tall RC columns may thus be excessively loaded by these seismic forces. Ensuring the rigorously controlled seismic integrity of the connections between the RC columns and the heavy RC roof beams is imperative for the overall seismic resilience of the precast structures. Traditional connections in precast structures, typically comprising two vertical pins and a horizontal anchor, are generally standardized. However, precast structures located within regions of high seismic activity necessitate a bearing capacity exceeding that provided by conventional RBC connections. Prior experimental research has demonstrated that the customary methods for enhancing the bearing capacity of RBC connections are rather ineffective, yielding a mere 8–15% increase (as indicated in Table 1). Given that precast structures are situated in varied seismic zones—ranging from low (A_{max} < 0.2 g) to medium (A_{max} = 0.2–0.4 g) to extremely high seismic intensity (A_{max} = 0.5–0.8 g)—the seismic-bearing capacity of the connections must correspond to the heightened demands imposed by increased seismic forces. This necessity is underscored by the extensive damage and complete collapse of industrial halls previously observed. Historically, the development of advanced methods for the enhancement of existing RBC connections has not been thoroughly explored, and effective technical solutions are yet to be introduced.

The research delineated in this manuscript is acutely centered on the innovation of a specialized seismic augmentation technique for N precast RBC connections utilizing adaptable SSK devices. Comprehensive experimental and analytical inquiries have led to the examination of several salient subjects, which are methodically discussed herein. These include: (1) the efficiency of original and conventionally upgraded RBC connections; (2) the design of novel SSK device prototypes; (3) the effectiveness of RBC connections upgraded with adaptable SSK devices; and (4) a synthesis of key findings pertinent to the practical implementation of the innovative technology devised for the upgrading of original RBC connections.

3. Performance of Original and Classically Upgraded RBC Connections

3.1. Prototype Structure and Experimental Testing

The considered prototype structure of the studied precast N system in this investigation consisted of a symmetric frame system rectangular in plan. The structure contained four RC columns, forming in the transverse direction three equal spans of 20.0 m each. In the longitudinal direction, 12 equal spans of 6.0 m with designed threaten RC columns were formed. Having dimensions of 60 m by 156 m, the structure covers a total area of 9,360 m^2. All precast columns were fixed to the installed precast foundations with dimensions of 3.0 × 3.0 m or 4.0 × 4.0 m, depending on the existing vertical load. The columns were designed with identical cross-sections of 60 cm × 60 cm and with identical concrete classes. Longitudinal reinforcements of the perimeter and interior columns consisted, respectively, of 12ϕ20 and 12ϕ25 mm steel bars. In the two cases, the reinforcing ties were ϕ8/12 cm and ϕ10/15 cm, respectively. The roof structure in the transverse direction was formed of precast RC roof beams having a height of 140.0 cm and a span of 20.17 m, and of precast RC roof beams having a height of 134.35 cm and a span of 20.0 m. The remaining elements of the roof structure were secondary elements. The heights of the central and perimeter columns were 8.67 and 8.08 m, respectively. Regularly, embedded pin (EP)-based RBC connections have been implemented in the considered precast N systems. These original (ORBC) connections have been in use for a long time. However, experimental data verifying and confirming their real nonlinear behavior, including specific damage patterns or total failure mechanisms, are not available. Additionally, no experimental data exists that can be considered reliable for the correct evaluation of the increased safety level with implemented classical upgrading method of URBC connections. Consequently, conducting realistic analysis and obtaining reliable insight into structural safety in the event of an extremely strong earthquake is not possible. Therefore, the extensive experimental and analytical investigations that were conducted by the authors are highly important and indispensable. The real nonlinear characteristics of the implemented original RBC connections and those of the classically upgraded original URBC connections were experimentally confirmed in detail [34–36], providing conditions for the extension of our innovative development presented in this paper. The results obtained from the initially realized experimental and analytical study led to important conclusions. The research gap related to the future practical implementation of precast N structures in seismic zones with the highest intensity was clearly confirmed. Therefore, to maintain the related research continuity, the respective summary of the obtained original experimental test results is presented briefly, which were directly considered as the major existing background outcome, fully supporting the present extended innovative research.

3.2. Original Roof Beam–Column Connection: The M4-A Prototype Model

The test prototype model M4-A, representing the original RBC connection, was designed and constructed at a large scale (1:2) to provide a realistic simulation of the actual nonlinear behavior characteristics of the real prototype connection (Figure 1, left).

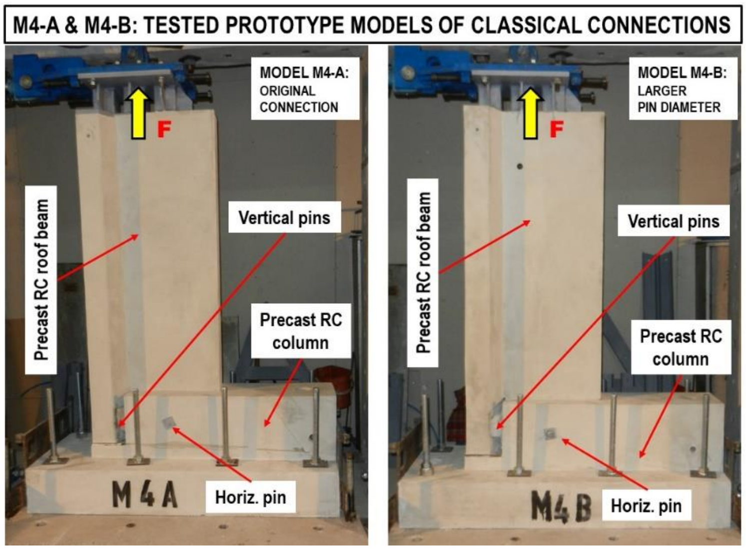

Figure 1. Tested prototype models M4-A and M4-B with classical roof beam–column (CRBC) connections

With the large-scale design of the testing model of the connection, significant advantages are assured. (a) The concrete of the model was used with the same characteristics as the concrete of the prototype; (b) the used reinforcements were also identical and adopted only by scaling; (c) the test model was designed only by scaling the geometrical characteristics; and (d) the original test results are of high reliability. The full-scale prototype of the RBC connection was installed with two identical vertical and one horizontal anchor. The two vertical anchors had a diameter of 25 mm, resulting in a total cross-sectional area of 9.82 cm^2. The horizontal anchor had a diameter of 25 mm and a cross-sectional area of 4.91 cm^2. To provide the additional safety of the common connection, it was installed in the common horizontal opening with a diameter of 27 mm [36]. Following the related similarity rule, the scaled prototype model of the original connection was successfully designed. The two vertical anchors had a diameter of 12 mm, resulting in a total cross-sectional area of 2.26 cm^2. The horizontal anchor was designed with a diameter of 12 mm and a cross-sectional area of 1.13 cm.

3.3. Classically Upgraded Roof Beam–Column Connection: M4-B Prototype Model

The tested M4-B prototype model, representing a classically upgraded RBC (URBC) connection, was also designed on a large scale (1:2, Figure 1, right). For the tested model of the upgraded connection, the following three improvements were implemented: (a) the diameter of the two vertical steel anchors was increased to 16 mm, resulting in a combined cross-sectional area of 4.02 cm^2; (b) the diameter of the horizontal anchor was increased to 16 mm, having a cross-sectional area of 2.01 cm^2; and (c) the confinement of the concrete in the zone of the embedded anchor was significantly improved by the installation of additional bars and confining hoops. The constructed M4-A and M4-B prototype models were identically experimentally tested based on identical testing conditions. The same experimental laboratory testing frame was used to comparatively evaluate the nonlinear response performances of both connection options.

3.4. Limitations of Existing Roof Beam–Column Connections

Based on the results obtained from extensive experimental and analytical studies conducted by the authors [36], the following important and original conclusions were summarized:

- The tested connection formed based on applying an EP system has generally shown good performance and can be practically used in seismic zones in which the generated seismic forces will not exceed the yielding force FY, representing the bearing capacity of the connection.
- In cases where the generated seismic forces are negligibly higher than the yielding force (e.g., 3–5%), only fine cracks up to 5 mm will occur in the concrete. The connection will remain completely compact, providing a satisfactory seismic safety level, as shown in Figure 2.

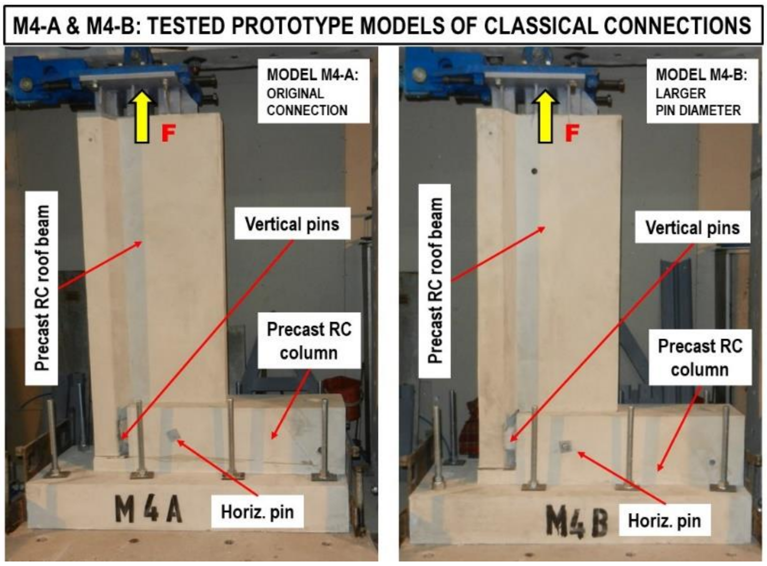

Figure 2. Safe response of CRBC connections for limited displacements (5–6 mm)

- In cases where the connection experiences deformations greater than 5 mm, only the maximum resisting force will be negligibly reduced. The connection is experimentally confirmed to show satisfactory ductility, as evident from Figure 2. However, for induced larger deformations, intolerably large cracks will occur in the concrete. The concrete will be completely crushed locally, particularly in zones exposed to the highest stress concentrations. These critical response modes will occur in the case of ORBC and URBC connections.

With the results obtained from the tested M4-B prototype model, the classical upgrading method was confirmed to be incapable of providing a satisfactory upgrading effect. Generally, the classical upgrading method can provide only a limited increase in the bearing capacity of the connection. Due to the severe degradation of the connection, including the crushing of concrete, the maximum increase in the bearing force of the connection was limited to only 15–20% (Figure 3 and Table 1).

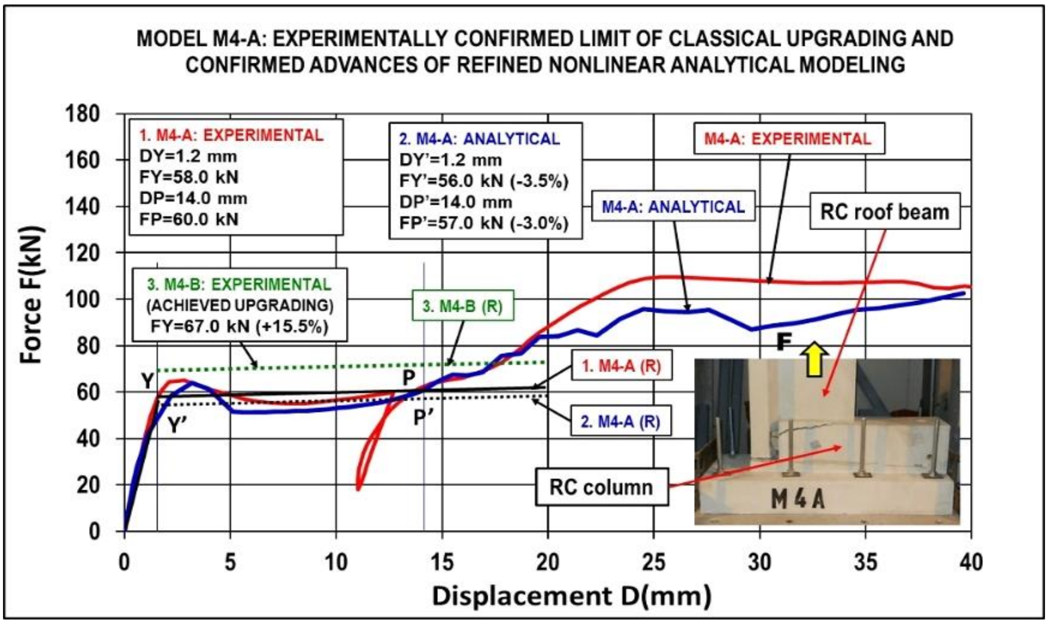

Figure 3. Prototype Model M4-A: Confirmed limitations of classical upgrading concept of RBC connections and confirmed advances in refined nonlinear analytical modeling

Table 1. Parameters of bilinear models of original and classically upgraded connection prototypes

No.	Prototype of tested roof beam–column connections					
	Original Connection			Classically Upgraded Connection		
1	*DY* [mm]	4.0	Exp.	*DY* [mm]	8.0	s.v.
2	*FY* [kN]	232.0	Exp.	*FY* [kN]	268.0	+15.5%
3	*DP* [mm]	29.0	Exp.	*DP* [mm]	36.0	-
4	*FP* [kN]	236.0	Exp.	*FP* [kN]	288.0	+22.05%
5	K_0 [kN/mm]	58.0	Exp.	K_0 [kN/mm]	33.5	s.v.

Regarding the experimentally confirmed severe limitation of the classical upgrading methods, the existence of the important research gap was clearly confirmed. To address this, extended research must be conducted, and a qualitatively improved upgrading method must be developed that is capable of providing a much higher bearing capacity for the connection. Creation and practical application of the more efficient and reliable upgrading method of RBC connections are particularly essential for cases where the precast structure is located in zones with extremely high seismic intensity. Therefore, our extended study focused on the development of technically and practically advanced upgrading solutions for RBC connections, representing a significant and important research step toward successfully overcoming this evident research gap.

4. Prototype Models of Adaptive SSK-1 and SSK-2 Upgrading Devices

The need to develop improved technology to upgrade the original RBC connections was identified, confirming that (1) the classical upgrading concept does not provide a significant increase in bearing capacity; (2) the seismic response of the original connections only showed satisfactory safety if the deformations at the connection when exposed to tension remained within the domain of linear behavior; and (3) if deformations became larger under very strong earthquakes, the connection would experience intolerable destruction or total failure owing to large cracks and crushing of the concrete.

The present innovative concept for upgrading RBC connections was created based on an incorporation of the originally introduced respective mechanical "force-transmitting segment," created in two geometrically distinctive optional solutions. The transmitting segments of the upgraded devices, named the seismic safety key-1 device (SSK-1 device) and seismic safety key-2 device (SSK-2 device), developed in this study reflect these two different solutions.

4.1. Prototype Models of SSK Upgrading Devices

The prototype model for the upgraded SSK-1 device integrated a load-transmitting segment in the form of a straight rectangular steel element, Figure 4, right, with a length of 220 mm and cross-sectional dimensions of 25 mm width and 10 mm thickness, Figure 5(a) and Figure 5(b).

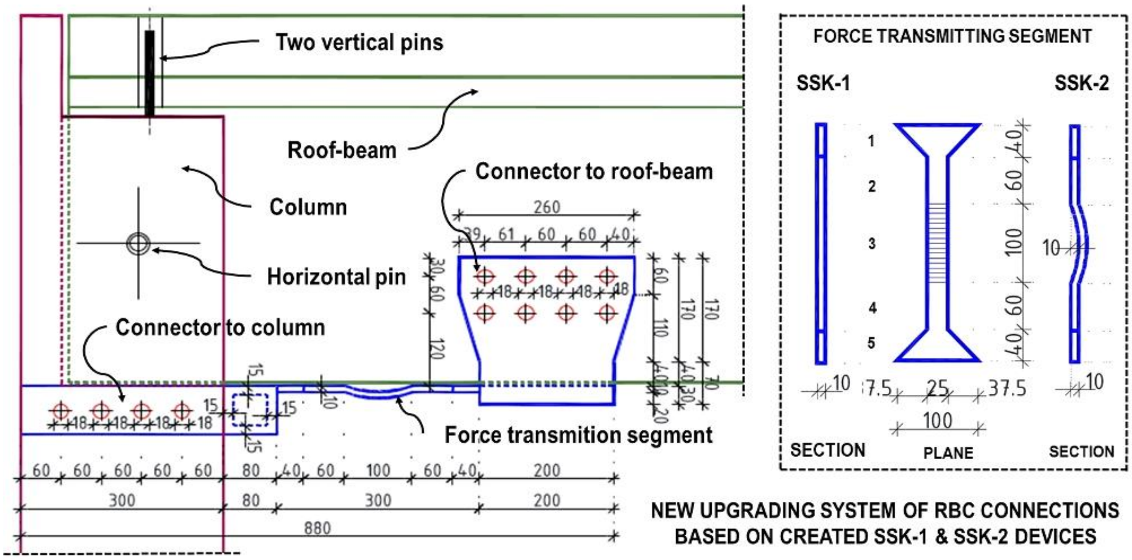

Figure 4. Concept of adaptive upgrading system of RBC connections based on installation of the innovative SSK-1 and SSK-2 devices created in this study

On both sides, the force-transmitting segment was elongated using trapezoidal steel elements with a length of 40 mm, sides of 25 and 100 mm, and a thickness of 10 mm. The trapezoidal steel elements were fixed to a specially designed connector on the roof beam and a connector on the column (Figure 4). The roof beam steel connector is composed of two cover metal plates with appropriate shape and dimensions, placed on the two faces of the roof girder and fixed to it with eight appropriate bolts ϕ18 mm, enabling the transfer of any axial force or moment generated. On the other end, the trapezoidal steel element is fixed to a rigid metal tube-like element with a square cross section of 80 × 80 mm and a wall thickness of 40 mm. The metal tube was laterally connected to the metal plates placed on both faces of the RC precast column. The two metal cover plates are fixed to the RC column with four bolts ϕ18 mm, forming a corresponding column connector (Figure 4). For the SSK-2 device, the load-transmitting segment was designed in the form of a curved rectangular steel segment, Figure 4, with a length of 220 mm and the same cross-sectional dimensions, with a width of 25 mm and a thickness of 10 mm, Figures 5(c) and 5(d).

A curved rectangular load-transmitting steel segment with the same width of 25 mm was designed to integrate the three steel parts along its length. The middle part was designed with a length of 100 mm and created in a lightly curved form with a small arch camber of only 10 mm. At both ends, the curved part continues with completely straight segments with a length of 40 mm and the same width of 25.0 m, as shown in Fig. 4. The remaining components of SSK-2 were identical to those of SSK-1.

4.2. Testing of The SSK Upgrading Devices

Testing of the SSK-1 device: An experimental test of the straight load-transmitting segment we created was conducted under gradually increasing tension deformation, simulating one-way loading (OWL), as shown by L11 in Figure 5-a. The resulting force-deformation relationship for the SSK-1 device showed a bilinear shape. The experimental relationship obtained for the SSK-1 device is shown in Figure 6, along with the defined parameters of the representative bilinear analytical model.

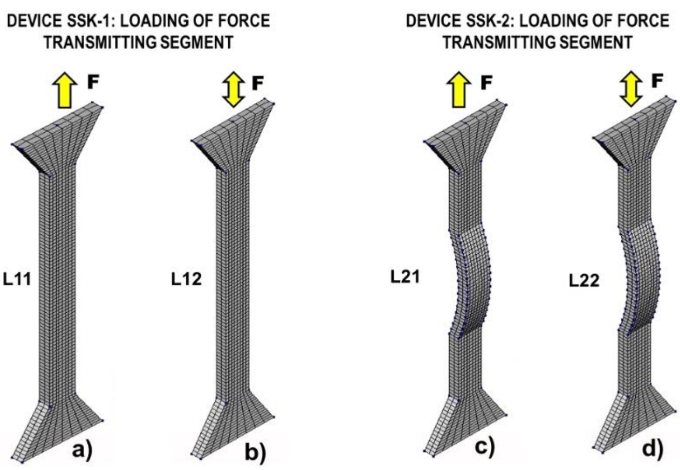

Figure 5. Force-transmitting segments of the SSK-1 and SSK-2 devices with simulated loading cases

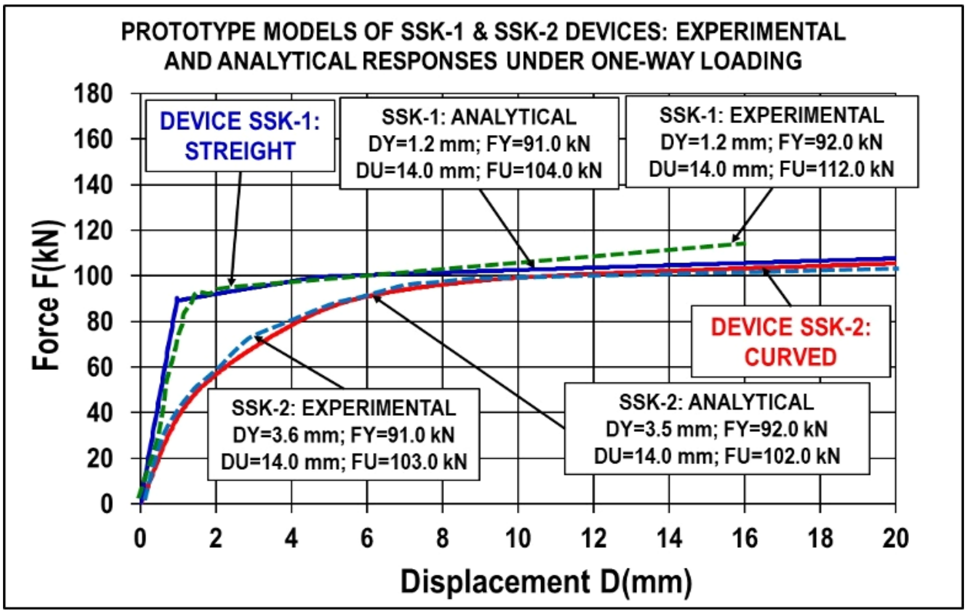

Figure 6. Experimentally and analytically defined responses of prototype models of the SSK-1 and SSK-2 devices under simulated one-way loading

Testing of the SSK-2 device: The experimental test of the curved load-transmitting segment we created was also conducted under gradually increasing tension deformation, simulating the OWL, as shown by L21 in Figure 5-c. The obtained force-deformation relationship for the SSK-2 device was modified and represented a nonlinear response, even in the case of small deformations. A nonlinear relationship is shown in Figure 6, along with the defined parameters of the representative bilinear analytical model.

4.3. Analytical Modeling of the SSK Upgrading Devices

Modeling of the SSK-1 device: Using the formulated advanced nonlinear micro analytical model shown in Figures 5-a and 5-b, an original response analysis of the SSK-1 device was first conducted to understand the effect of the simulated OWL. The experimental and analytical relationships obtained agree very well since the difference obtained in the yielding force FY amounted to only −1.1%, while that in the ultimate force was only −7.6% (Figure 6). Using the same analytical model, the response of the SSK-1 device to the effects of the simulated cyclic loads, as shown in Figure 5-b, defined as the specific L12 loading, was also computed.

The two nonlinear responses of the SSK-1 device, which has a straight load-transmitting segment computed under simulated one-way loading (OWL) and cyclic loading (CL), are shown in Figure 7 (left). The envelopes of the tensile side obtained under OWL and CL almost overlap, indicating the excellent reliability of the results.

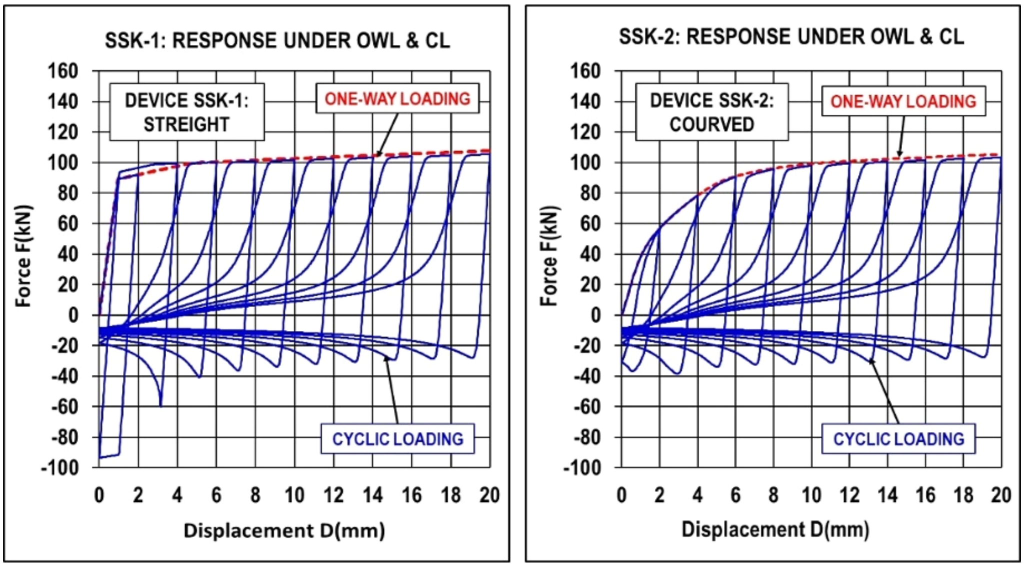

Figure 7. Characteristic responses of prototype models of the SSK-1 and SSK-2 devices under simulated one-way and cyclic loading

Modeling of the SSK-2 device: Using the formulated advanced nonlinear micro analytical model (Figures 5-c and 5d), an original response analysis of the SSK-2 device was first conducted to understand the effect of the simulated OWL. The obtained experimental and analytical relationships were also in agreement, since the difference obtained in yielding force FY amounts to only 1.1%, while the difference in ultimate force FU is only −1.0% (Figure 6). Using the same analytical model, the response of SSK-2 under the effect of simulated cyclic loads, as shown in Figure 5-d, which is defined as the specific L22 loading, was also computed.

The two nonlinear responses of the SSK-2 device, which had a curved load-transmitting segment computed under simulated one-way and cyclic loadings, are shown in Figure 7 (right). It was also confirmed that the shapes of the experimental and analytical relationships for SSK-2 were highly correlated.

4.4. Performances of Novel Roof Beam–Column Upgrading Devices

The experimental and analytical studies enabled the definition of the basic parameters characterizing the specific responses of novel SSK-1 and SSK-2 upgrading devices: (1) The SSK-1 device provides high initial stiffness and small initial deformations. For larger deformations, the efficiency is preserved and remains undisturbed, and the SSK-2 device provides an adaptable (variable) initial stiffness and negligibly larger initial deformations. In the case of larger tensile deformations, its efficiency is also preserved; (3) both created options of SSK devices provide satisfying conditions for use in practice; and (4) this conclusion was confirmed by the original study of the seismic performances of upgraded RBC connections with the novel SSK-2 device.

5. Performance of Upgraded Roof Beam–Column Connections using SSK-2 Device

5.1. Upgrading Concept with the SSK-2 Device: Prototype Model M4-A*

The nonlinear response characteristics of the ORBC connection under simulated one-way and cyclic loading conditions have been fully understood in previous studies [29]. In the present study, the main research was focused on determining the nonlinear response of the URBC connection using a novel SSK-2 device. To enable a direct comparison of the obtained results, the same original prototype model was converted into an SSK-2-upgraded original RBC connection, representing model M4-A* (Figure 8).

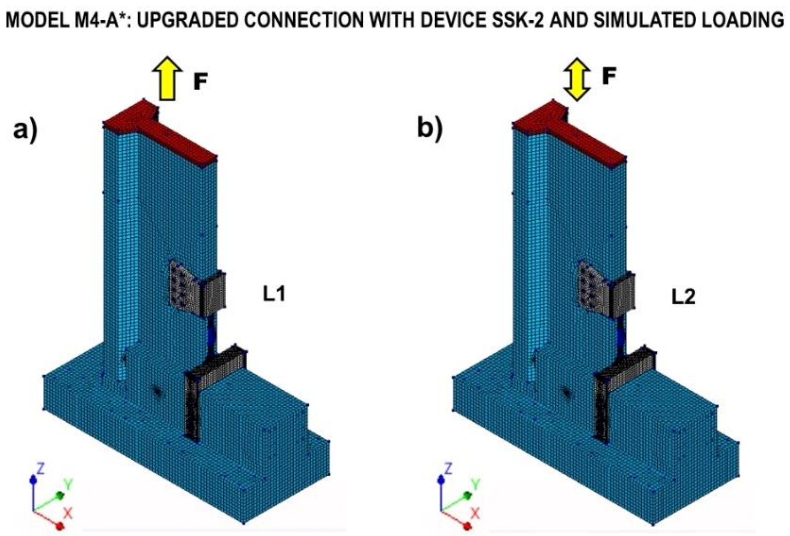

Figure 8. Formulated refined nonlinear analytical model and simulated characteristic loading cases of upgraded RBC connection M4-A* with the adaptive SSK-2 device

Thus, the SSK upgrading concept was significantly simplified. It is based on the direct application of the developed SSK-2 upgrading device and its fixation to the existing RC roof beam and RC column through the developed respective RB-connector and C-connector.

5.2. Refined Modeling of Upgraded Connection M4-A

Extensive analytical studies were conducted using the formulated refined nonlinear analytical model of the novel prototype M4-A*, which represents an SSK-2-upgraded RBC connection. Analytical studies were conducted under simulated OWL (L1) and CL (L2) conditions, as shown in Figures 8-a and 8-b, respectively. This study resulted in a complex computational process involving the solution of large three-dimensional nonlinear analytical problems. The analytical studies were successfully realized using DIANA FEA (2016) [30], a finite element software that is currently among the most powerful software packages available for this type. The finite elements used to model RC segments, steel segments, connection segments, and the integral SSK-2 devices were small; specifically, the concrete nonlinear finite elements used were three-dimensional solid "semi cubes" with proportions of the order of 2 cm × 2 cm × 2 cm that varied only slightly, depending on their location. Because of the implementation of the advanced three-dimensional micro-modeling concept, the total number of finite elements, nodal points, and degrees of freedom became large. Consequently, the solution to a large system of nonlinear equations becomes extremely complex, particularly because of the equilibrium iterations at each individual solution step.

5.3. Refined Modeling of Concrete, Steel, and the SSK-2 Device

To realistically simulate the different specific segments of the M4-A* connection, five types of nonlinear finite elements (FE) were implemented: (a) FE representing the concrete material; (b) FE of type-1 steel, characterizing the steel material of the connection anchors; (c) FE of type-2 steel, representing embedded steel reinforcement; (d) FE representing the zero-tension interface connection (simulating the complex contact conditions of the horizontal unbounded anchors); and (e) FE representing the steel material used for assemblage of the integral structure of the novel SSK-2 device.

The material characteristics used in the analytical model were obtained from standard tests conducted on corresponding material samples. The following material characteristics were considered when formulating the refined nonlinear analytical model of the M4-A* connection in DIANA FEA (2016) software [30].

The nonlinear concrete model had six specified parameters: concrete class C45; Young's modulus E_c = 3,628.3 kN/cm^2; Poisson's ratio $\gamma_c = 0.2$; mass density $g_c = 2.4 \times 10^{-8}$ kNs^2/cm^4; tensile strength *f'* = 0.421 kN/cm^2; compressive strength f_c = 4.8 kN/cm^2. Furthermore, the following were adopted: a crack model based on total strain, rotating crack orientation, tensile curve defined as the Japan Society of Civil Engineers (JSCE) tension stiffening, compression Maekawa Cracked Concrete curves, and the confinement model proposed by [30, 31].

The nonlinear model of type-1 steel (steel connecting anchors) had the following specifications: Young's modulus $E_s = 2 \times 10^4$ kN/cm^2; Poisson's ratio $\gamma_s = 0.3$; mass density $g_s = 7.85 \times 10^{-8}$ kNs^2/cm^4; and selected isotropic strain hardening. The nonlinear model of type-2 steel (steel reinforcement) had the following specifications: Young's modulus E_s = 19466 kN/cm^2; Poisson's ratio $\gamma_s = 0.3$; yield stress σ_y = 43.263 kN/cm^2, mass density $g_s = 7.85 \times 10^{-8}$ kNs^2/cm^4; and the Menegotto–Pinto nonlinear behavior simulation model. The zero-tension interface connection had the following specifications: normal stiffness modulus (z direction) K_{nz} = 100.0 kN/cm^3; shear stiffness modulus (x direction) K_{sx} = 100.0 kN/cm^3; shear stiffness modulus (y direction) K_{sy} = 100.0 kN/cm^3.

Finally, the nonlinear model of type-3 steel (SSK-2 device steel) had the following specifications: Young's modulus $E_s = 2 \times 10^4$ kN/cm^2; Poisson's ratio $\gamma_s = 0.3$; mass density $g_s = 7.85 \times 10^{-8}$ kNs^2/cm^4; and selected isotropic strain hardening.

5.4. Analytical Simulation Results for the Upgraded M4-A* Connection

Following the refined nonlinear response analyses conducted for the upgraded connection with the SSK-2 upgrading device, represented by the prototype model M4-A*, for simulated one-way and cyclic loading, a large volume of analytical results was obtained and analyzed. The large variety of figures showing the specific response results and related video recordings clearly indicate consistent results for the modeled concrete segments, embedded steel anchors, unembedded steel anchors, reinforcing steel segments, modeled complete novel SSK-2 device, and integral prototype model of the SSK-2-upgraded original RBC connection. Detailed results were obtained, allowing the consideration of separate segments of the model, including the history of displacements, crack propagation, stress, and strain fields. Fig. 8 shows the integral nonlinear micro analytical model formulated for the novel M4-A* prototype connection, representing the original connection upgraded by the SSK-2 device.

The two simulated loading patterns representing OWL and CL are respectively indicated in Figures 8-a and 8-b. Figures 9-a and 9-b show the propagation of the total Cauchy stresses SZZ in the integral upgrading device and in detail in the enlarged force-transmitting segment, respectively. Figure 10 (left) shows the typical simulated Cauchy total stresses in the reinforcing steel, whereas Figure 10 (right) shows the recorded critical and cracked zones of the concrete.

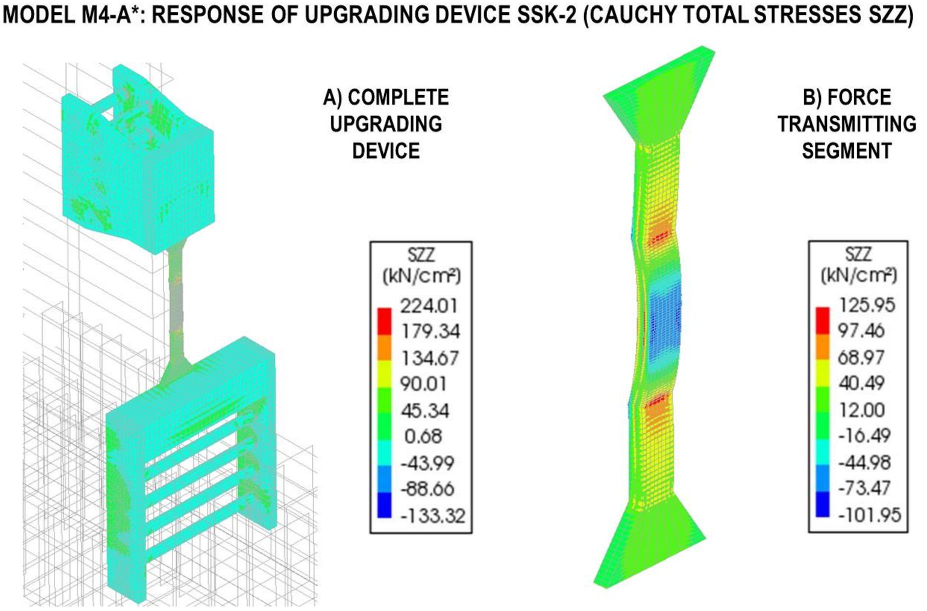

Figure 9. Response of Model M4-A* representing upgraded RBC connection with SSK-2 device: Typical total stresses pattern SZZ for complete upgrading device and force-transmitting segment

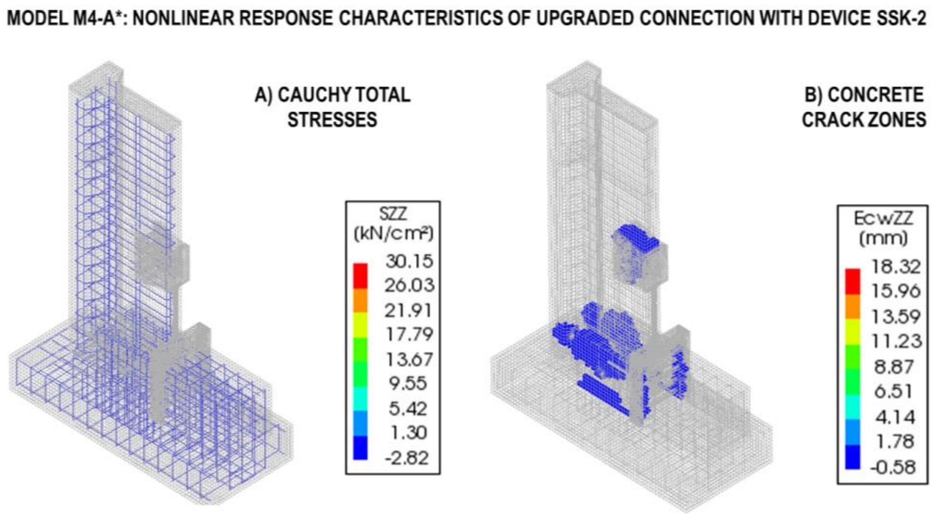

Figure 10. Response of Model M4-A* representing upgraded RBC connection with the SSK-2 device: Typical total stresses pattern SZZ for reinforcement and dominant concrete crack zones detected

Considering the experimental and analytical results obtained for the original connection and the upgraded original connection with the novel SSK-1 and SSK-2 upgrading devices, the resulting upgrading effects are defined and presented in Table 2.

Table 2. Defined parameters of bilinear models for SSK-1 and SKK-2 upgraded roof beam–column connections

No.	Prototype models of upgraded roof beam–column (RBC) connections					
	SSK-1 upgraded RBC connection			SSK-2 upgraded RBC connection		
1	DY [mm]	4.0	s.v.	DY [mm]	5.6	s.v.
2	FY [kN]	596.0	+156.8%	FY [kN]	528.0	+127.5%
3	DP [mm]	28.0	-	DP [mm]	28.0	-
4	FP [kN]	684.0	+189.8%	FP [kN]	640.0	+166.6%
5	K_0 [kN/mm]	149.0	s.v.	K_0 [kN/mm]	94.3	s.v.

For example, regarding the connections upgraded with the SSK-1 device, the connection strength controlling forces FY* and FP* increased significantly, by +156.8% and +189.8%, respectively (Table 2). Similarly, in the case of connections upgraded with the SSK-2 device, the strengths of the connection forces FY* and FP* also increased by +127.5% and 171.1%, respectively (Table 2). Following the original results obtained using the micro analytical model to analyze the upgraded original connection with the SSK-2 device, the upgrading effects obtained in the case of the simulated OWL and CL are presented in Figures 11 and 12, respectively. The results clearly demonstrate the large upgrading effects obtained, amounting to increases of +127.5% in the upgraded FY* force and +166.6% in the upgraded FP* force. The graphically presented results clearly show a significant improvement in the strength and ductility of the innovatively upgraded original RBC connections (Figures 11 and 12). From the experimental and analytical results related to the nonlinear performance of the innovatively upgraded original RBC connection with the new SSK-1 and SSK-2 upgraded devices, the following conclusions can be drawn:

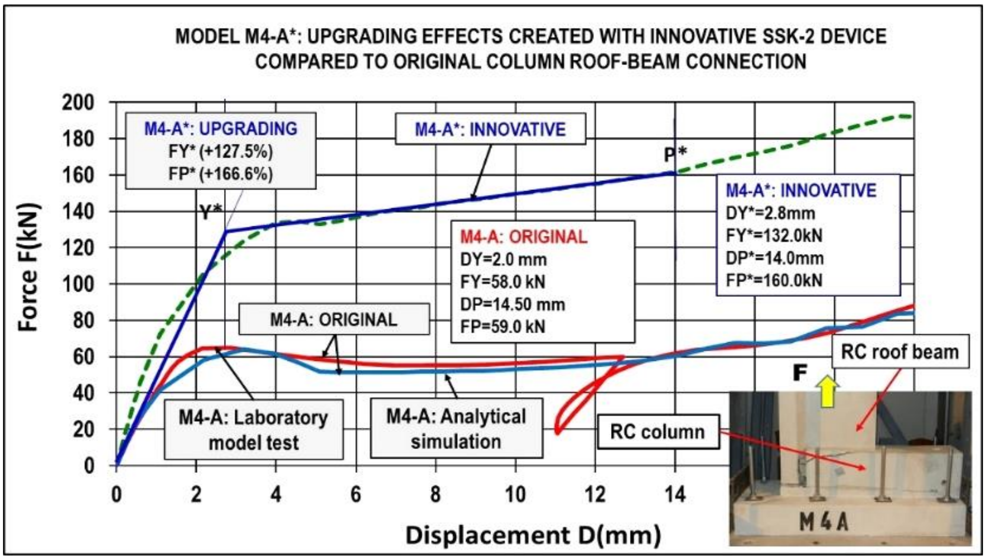

Figure 11. Model M4-A* representing upgraded RBC connection with SSK-2 device: Upgrading effects with the SSK-2 device compared to the actual performance of the original RBC connection

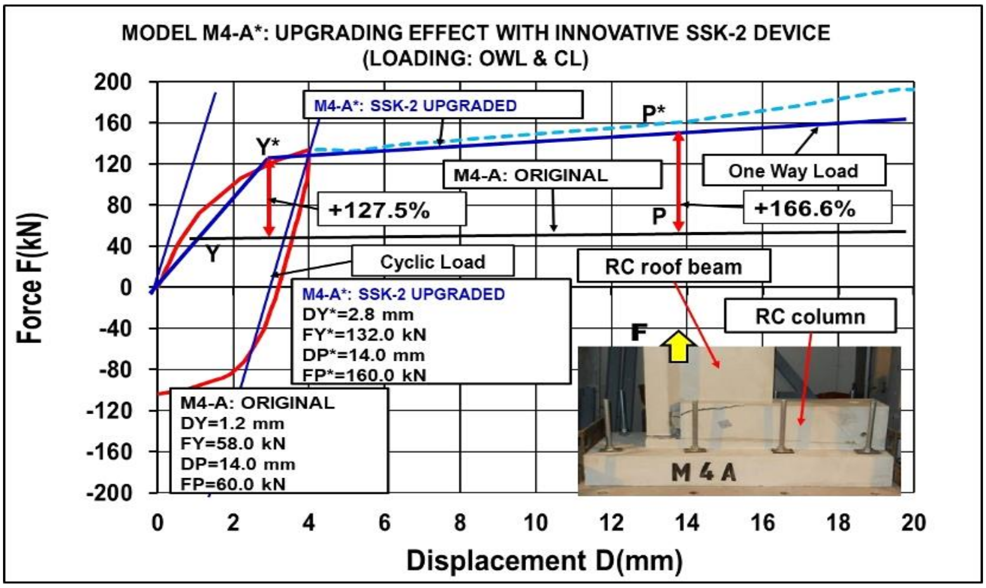

Figure 12. Model M4-A* representing upgraded RBC connection with SSK-2 device: Confirmed actual upgrading effects with the SSK-2 device under simulated one-way and cyclic loading

5.5. Advances of SSK-Based Upgrading Method

Regarding the effects of strong destructive earthquakes, the real safety advances of the precast structure designed with SSK-based upgraded RBC connections (structure S2) with respect to the structure designed with ORBC connections (structure S1) were deeply studied analytically. To briefly present the confirmed qualitative differences, only key comparative results are included. The original experimental tests confirmed the actual nonlinear response characteristics of all respective types of RBC connections, including (1) the original RBC connection, (2) the classically upgraded original RBC connection, and (3) the two options of a novel SSK-based upgraded RBC connection. Considering the test results, reliable, representative bi-linear analytical models were formulated for all connection types. The seismic responses of precast structures S1 and S2 were analyzed by simulating four real strong earthquakes, including: (1) El Centro, PGA = 0.50 g; (2) Ulcijn Albatros, PGA = 0.50 g; (3) Landers, PGA = 0.50 g; and (4) Northridge, PGA = 0.50 g. The used parameters of the formulated bi-linear analytical models for both connections are given in Tables 1 and 2, respectively.

a) ***Nonlinear models of precast structures*:** The advanced tri-dimensional nonlinear analytical models of the analyzed precast structures S1 and S2 were formulated considering the given geometry of the prototype structure, actual material properties, characteristics of the assembled precast structural members, and the confirmed bearing capacity of the implemented connections. For the precast structural elements, including columns, roof beams, and secondary beams, concrete C40 was used. The advanced fiber modeling concept was used for the nonlinear behavior modeling of the implemented RBC connections, which were modeled by the respective nonlinear link elements. considered columns as fixed to the precast footings. The cross-sections of the columns were represented with 488 fibers and used respective stress-strain models of confined concrete, unconfined concrete, and steel fibers. The implemented RBC connections were modeled by the respective nonlinear link elements.

b) ***Seismic response studies*:** A full set of original nonlinear response parameters were defined from analytical studies of both structures, including: (1) dynamic characteristics; (2) time-history responses of displacements, velocities, and accelerations; (3) nonlinear responses of precast RC columns; (4) nonlinear responses of critical connections, etc. The computed vibration periods of the first three structural modes amounted to T1 = 0.856 s, T2 = 0.780 s, and T3 = 0.761 s, while their modes were expressed in x, y, and torsion directions, respectively.

c) ***Advances of the SSK-based Upgrade Method*:** The most critical seismic response of both precast structures, S1 designed with original RBC connections and S2 designed with SSK-2-upgraded connections, was observed under the simulated Northridge earthquake with PGA = 0.5 g. In the case of structure S1, the analytical results indicated an unsafe or critical nonlinear response of the connections (Figure 13). Due to the induced failure of the connections, the total collapse of the structure is expected. However, in the case of structure S2, having upgraded connections with novel SSK-2 devices, all connections were completely safe. To clearly express the advances achieved by the SSK-based upgrading method, the precast structure S2 was analyzed again, considering a much stronger earthquake represented by PGA = 0.7 g. However, the upgraded connections with novel SSK-2 devices were fully safe, showing pure linear behavior (Figure 14). By applying the created technology, the targeted seismic safety level was efficiently achieved, although the regular design procedure remained unchanged.

5.6. Upgrading of Design Provisions

The presented original results obtained from the realized experimental and analytical studies provide wide opportunities for efficient advancement of the present design codes. The advantage of the proposed upgrading method for RBC connections with the application of novel SSK devices was clearly confirmed. The targeted seismic safety level of the newly designed precast structures should be assured with the application of the previously experimentally attested SSK-upgraded RBC connections. Similarly, the seismic safety level of the existing vulnerable precast structures can be increased by applying the previously experimentally attested SSK devices.

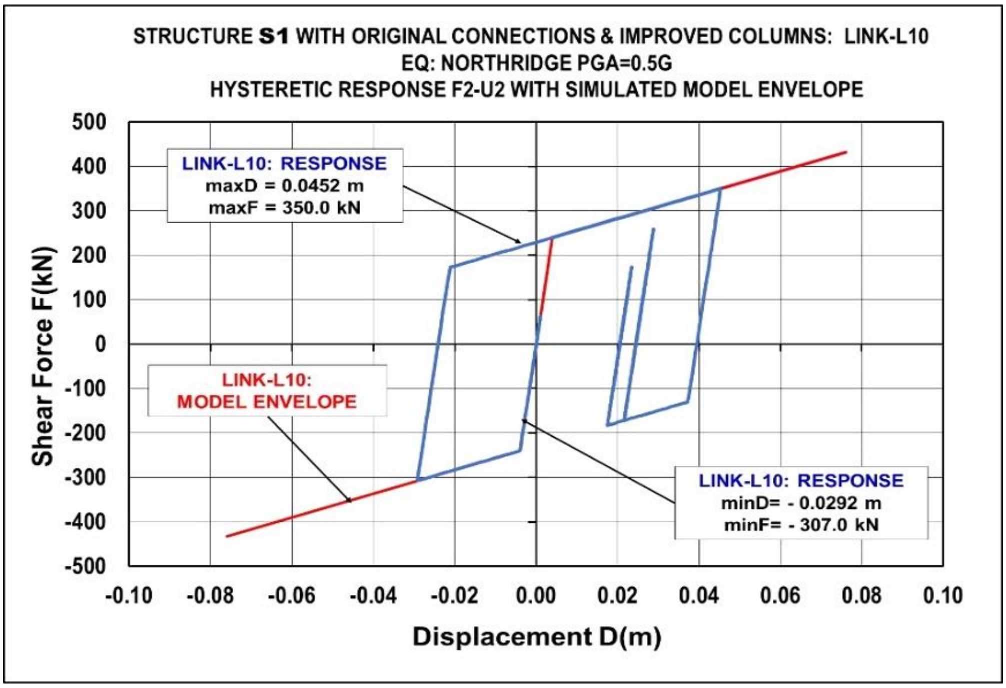

Figure 13. Seismic response of precast structure S1 with original connections under simulated Northridge earthquake (direction-x, PGA = 0.50 G): Hysteretic response of critical RBC connection, link-L10

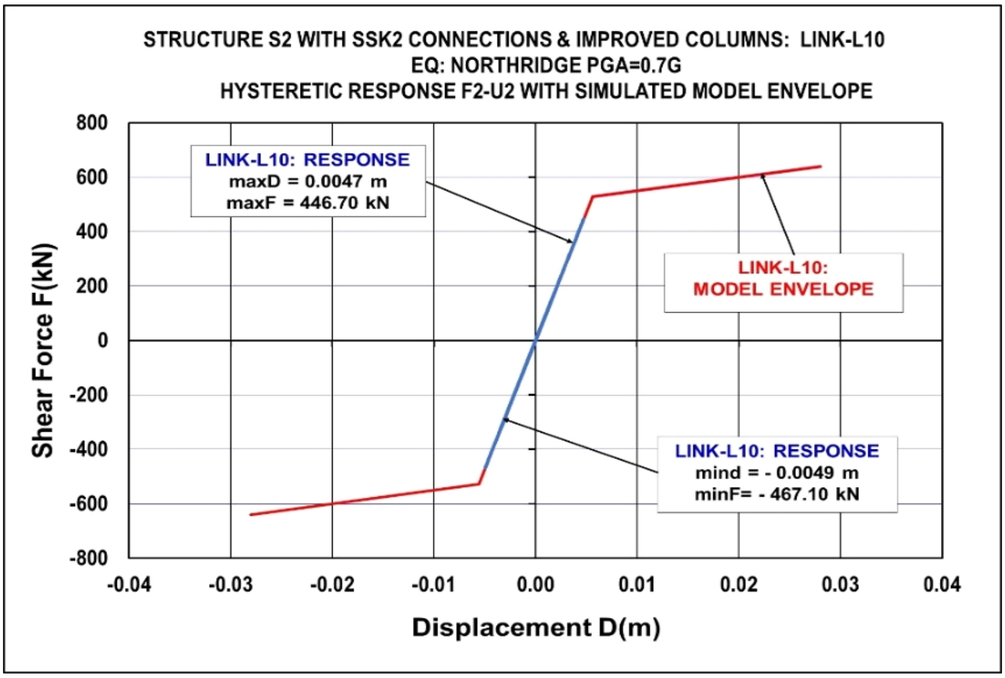

Figure 14. Seismic response of precast structure S2 with SSK-2-upgraded connections under simulated Northridge earthquake (direction x. PGA = 0.70 g): Hysteretic response of critical RBC connection, link-L10

6. Conclusions

From the experimental and analytical results related to the nonlinear performance of the innovatively upgraded original RBC connection with the new SSK-1 and SSK-2 upgraded devices, the following conclusions can be drawn:

- The existing (original) RBC connections of the precast N system possessed a regular and uniform bearing capacity. However, if seismic forces stronger than the actual capacity of the connection are induced, the connections may be exposed to serious damage or even total failure. Because classical upgrading methods can provide only limited upgrading effects, ranging between 15% and 20%, they are not completely reliable as safety solutions.
- The newly developed and experimentally proven novel targeted method for upgrading the original RBC connections based on the specific SSK-1 and SSK-2 upgrading devices created for this study represents an efficient tool for targeted safety upgrades of the original RB connections.
- The novel SSK-1 upgrading device developed in this study, which has an integrated straight load-transferring segment, instantly acts as a strong linear element from very small tensile deformations to its known targeted load-bearing capacity.
- The novel SSK-2 upgrading device developed in this study, with an integrated curved load-transferring segment, acted adaptively as a nonlinear element, even for very small tensile deformations, up to its known targeted load-bearing capacity.
- The specific nonlinear behavior characteristics defined experimentally for the SSK-1 and SSK-2 upgrading devices created in this study were successfully simulated analytically using the advanced nonlinear micro-analytical models formulated in this study. Both the SSK-1 and SSK-2 upgraded devices provided increases in bearing capacity up to the targeted level in the case of simulated effects of one-way and cyclic loading.
- The formulated nonlinear micro analytical model enabled a successful simulation of the nonlinear behavior of the integrally upgraded original RBC connection created with the innovative SSK-2 upgrading device under simulated one-way and cyclic loading. With the applied innovative upgrading method based on the installation of the SSK-2 upgrading device, the bearing force capacity of the new connection M4-A* increased drastically with respect to the bearing capacity of the original connection by +127.5% and +166.6% for the representative restoring forces FY* and FP*, respectively.
- The newly developed SSK-based seismic upgrading method for the original RBC connections provides advanced conditions for the design of upgraded connections with a targeted bearing capacity defined in close correlation with any possible higher level of induced seismic forces.
- The targeted upgrading method based on the SSK-1 and SSK-2 upgrading devices represents an innovative technology that can be practically implemented for the advanced seismic upgrading of unsafe existing RBC connections. The developed technology can be directly implemented for the rapid seismic upgrading of new and important existing precast structures located in seismically active regions, representing highly efficient practical activity specifically targeted at minimizing seismic risk.

7. Declarations

7.1. Author Contributions

Conceptualization, D.R.; methodology, D.R., J.R., and L.M.; software, L.M. and J.R.; validation, D.R. and V.H.; formal analysis, L.M. and J.R.; investigation, J.R., L.M., V.H., and D.R.; resources, D.R.; data curation, J.R.; writing—original draft preparation, D.R.; writing—review and editing, L.M. and J.R.; visualization, L.M. and J.R.; supervision, V.H.; project administration, J.R.; funding acquisition, D.R. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available upon request from the corresponding author.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Acknowledgements

The experimental research was conducted at the RESIN Laboratory in Skopje, established by Prof. D. Ristic, Partner Country Project Director of the Innovative Science for Peace and Security Project: Seismic Upgrading of Bridges in Southeast Europe by Innovative Technologies (SFP: 983828). In addition, the laboratory tests conducted were partially supported by PUT Inženjering Company, Nish, Serbia. Both types of research supports are highly appreciated.

7.5. Conflicts of Interest

The authors declare no conflict of interest.

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