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RESEARCH IMPERATIVES FOR ENHANCING THE ANALYSIS AND SEISMIC PERFORMANCE OF JOINTS IN VERTICAL BUILDING EXTENSIONS

Alush Shala [(1)], Jelena Bleiziffer [(2)]

[(1)] *Senior Project Manager, Alb-Architect L.L.C., 10000 Prishtina, Kosovo, alushala@gmail.com*
[(2)] *Assistant professor, Faculty of Civil Engineering Zagreb, jelena.bleiziffer@grad.unizg.hr*

Abstract

There are many cases around the world where vertical extensions of existing buildings are favored as alternatives to the erection of new buildings, which would entail demolishing the old structure as well. Such solutions with vertical extensions have certain benefits, but the design characteristics of the base structures and their condition after years of service urge careful consideration of the joint between the new and old structural members and how it affects the global performance of the entire system. The risk to human lives, as well as environmental, economic, and social implications – including pollution and carbon emissions contributing to the greenhouse effect – serve as a strong motivation for researching these connections. This issue becomes especially critical in regions prone to frequent tectonic activity, where errors in the design and execution of additional floors on existing buildings are often observed. The errors observed on-site during the execution and design of additional floors on existing buildings are notable. This paper will discuss the research needs for improving the seismic behavior of the structural detailing and subsequent modeling for structural analysis of this connection between the vertically added floors and the base structure, focusing on the reinforced concrete frame structure solutions. The connection between the new floor and the old structure might not be rigid as is often treated in the design phase, and the behavior of the joint in response to dynamic forces might differ from what is projected thus the joint might not be adequately addressed from a seismic behavior perspective. The treatment of this issue will be discussed taking into consideration the conditions in the on-site execution and the provisions of Eurocodes standards, namely the EC2 part 4.

Keywords: vertical extension, joint connection, seismic behavior, on-site execution

1. Introduction: background and research motivation

The observation of recent construction trends in the Republic of Kosovo, where it is a relatively frequent occurrence to erect additional floors on top of old buildings, raises concerns about their safety. Vertical extensions on old buildings pose higher risk than constructing the entire (higher) structure anew, especially so if executed beyond building permits, which may also happen in Kosovo, as there is a "widespread phenomenon of illegal buildings" [1]. These constructions violate current laws and regulations, making them illegal under existing legislation. Inspired by these developments and the need to address the impact of new construction on agricultural land, there was a motivation to explore innovative approaches to adding stories to existing buildings.

2. Preliminary review of the relevant research and numerical study

Although the research motivation stems from the experience and practices observed in Kosovo, the relevant research was reviewed to examine state-of-the-art around the world. An extensive discussion of the literature review is available from the previous publication [2]. A widespread interest was observed in various aspects of adding extra floors to buildings of various types, from more global and multicriteria and multidisciplinary perspectives, including:

- methods for adding floors to buildings considering the need for more space, associated costs, financial implications, and societal impacts [3],

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- global issue of increasing urban populations, emphasizing the risk to green spaces and productive land due to new construction, thus proposing adding new floors to old buildings [4],
- the reasons for adding extra floors to existing buildings, considering financial, social, and environmental factors, legal constraints, and permitting issues [5],
- the need to expand the capacities of existing structures due to significant population growth [5],

to the very specific ones, focusing on structural issues, for instance:

- analyses of the behavior, load-bearing capacity, and materials of old buildings, along with geometric aspects and foundation conditions for adding floors [7],
- examination of how to extend buildings constructed according to old building codes, utilizing elastic analysis and the capacity reserve in old structures [8],
- analyses of the joint connecting beams and columns, emphasizing its importance in a building's survival during seismic events [9],
- assessment of strengthening scheme of existing buildings extended by adding additional floors [10].

Overall, it was noted that the population growth worldwide drives the need for additional housing, and adding new stories to old buildings offers economic, environmental, and social benefits by eliminating the need to relocate residents temporarily. Environmental concerns also motivate exploring alternatives to demolishing existing structures, reducing financial costs and environmental impacts.

From the structural behavior and safety point of view, as the risks associated with adding floors and their response to the base building continue to rise, investigating the column-beam connection becomes crucial. The literature review [2] thus also encompassed the examples of treatment of similar structural details:

- the *fib* Task Group 6.2's guide Structural Connections for Precast Concrete Buildings explores connections between precast concrete elements, covering various connection types [11],
- Eurocode 2, Part 1-1 provides general rules and guidelines for reinforced concrete structures but does not address connections between columns and beams in superimposed elements [12],
- Eurocode 8, Part 1 focuses on design for earthquake resistance, including requirements for beam-column connections, including also the discussion on precast elements and their connections, specifying conditions for connection [13],
- ACI 550.2R-13 provides a design guide for connections in precast jointed systems, detailing conditions and behavior based on the type of joint and seismic zone [14]
- ACI 318-11 addresses connections in structural concrete [15],
- ACI 550.1R-01 covers various connections and seismic aspects in precast concrete structures [16]
- Eurocode 2, Part 4 focuses on the design of supplementary elements to be installed as structural or non-structural components, including anchoring with ribbed reinforcement in accordance with European technical regulations. It encompasses rules regarding the spacing of anchors and their distances from the edges of concrete members, as well as technical requirements for the load-bearing capacity of anchors and their modes of failure [17].

Following the preliminary review of the relevant research, it was decided to narrow the investigation to the connections between newly added floors of vertical extension and the old, existing building constructed as reinforced concrete (RC) frame structure. The earthquake risk further underscores the importance of researching this structural detail. Thus, a preliminary numerical study was conducted [2]. The assumption that these connections are monolithic, or rigid might not be held up in practice, as various factors affect their behavior, especially in seismic regions. The study demonstrated that under dynamic loads, new floors do not respond as if constructed simultaneously due to differences in materials and dowels anchoring. The design principle of strong columns and weak beams aims to ensure building stability. However, inadequately rigid connections between columns and old joints may lead to plastic hinge formation, jeopardizing the stability of added floors. The type of connection between the column and the old joint significantly influences the building's fundamental modes of oscillation. A

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significant motivation for addressing this phenomenon is the lack of clear guidance in codes regarding the effects of dynamic loads. No consensus exists on joint modelling techniques, despite extensive research, leaving room for improvement [18]. Similar concerns apply to joints on additional floors connected to old or base buildings. Retrofitting is a viable solution for most existing buildings that exhibit deficiencies and are vulnerable to future earthquakes. By using research findings and conclusions from various studies, the aim is to make a valuable contribution to addressing these structures, benefiting both society and the environment. This strong motivation drives to further develop this study on the connection between the new column and the old top column-beam node (corner frame joint), ensuring safety in existing multi-story buildings with added stories, as well as those to be constructed in the future.

3. Research objectives and hypotheses

The research objective is to investigate and address the challenges associated with adding new stories to existing buildings, particularly focusing on the connection between the new column and the old joint (corner frame joint in a RC frame structure). The aim is to understand the behavior of these connections, their impact on structural stability, and the response to dynamic loads, ultimately contributing to the safety and resilience of multi-story buildings. Specifically, the objectives are consequently formulated as follows:

1. analysis and assessment of joints in vertically extended RC buildings,
2. comparison of joint rigidity levels in joints connecting additional floors to an existing building under seismic influences,
3. determination of the joint rigidity coefficient in joints connecting additional floors to a base building for design purposes,
4. determination of the type of joint formation: fully rigid, semi-rigid or hinged,
5. determination of the load-bearing capacity of joints connecting additional floors to a base building,
6. evaluation of the advantages of constructing additional floors in existing and new buildings from economic, environmental, and social perspectives.

With research focusing on the new column and the old joint of the base building constructed as a RC frame structure, the hypotheses relate to the fact that the level of rigidity in this connection significantly impacts the structural stability and response to dynamic loads, thus rendering properly addressing this connection crucial for ensuring the safety of both existing and newly constructed multi-story buildings. The level of rigidity of the subject connection for RC frame buildings with added floors is not the same as for the new structures of the same number of floors, and therefore a coefficient that can be used to simulate the actual rigidity of the connection for calculation purposes when vertical extension of the structure is designed needs to be determined. The hypotheses were formulated as follows:

1. often-used assumption of full rigidity of a joint connecting vertical extension to an existing RC frame building is not accurate for construction practices in Kosovo and the region,
2. incorporating appropriate rigidity coefficients in the structural analysis of a vertically extended RC frame will provide a more realistic prediction of behavior under dynamic (seismic) loads.

4. Research plan and methodology

The following, six step research plan and program was put forward consisting of an experimental campaign to test scaled RC frame models and complementary numerical simulations, in line with the research objectives and hypotheses.

1. Firstly, the experiment's groundwork is laid, involving the preparation of experimental samples and models, thorough testing to assess the quality of the materials used, and the careful selection and calibration of testing equipment for reliable results.
2. Then the second step focuses on ensuring the validity of the experiment's outcomes. This involves not only the verification of results obtained from individual experiments through

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additional experiments but also a detailed analysis of results from similar experiments with analogies to the ongoing experiment. The establishment of experimental boundaries is crucial to guarantee validity and accuracy by thoroughly verifying the methodology used in obtaining results.

3. Moving on to the third step, numerical simulations and project methodology take center stage. Advanced computer methods will be employed for numerical simulations to analyze the behavior of connections at nodes and verify the design methodology. Additionally, the calibration of hysteretic shape parameters will be performed to establish a reliable relationship with experimental results.
4. The fourth step revolves around the exploration of various connection types. A diverse range, including those with anchoring and prefabricated elements with similarities, will be thoroughly examined. The implementation of connections is a critical aspect of this phase, serving to validate the design methodology of experimental connection. Furthermore, a specific connection will be proposed as an experimental solution, ensuring complete testing adequacy.
5. As progress to the fifth step is made, design guidelines will be proposed based on the technical rules and codes in force for design. These guidelines will be informed by the experimental findings, considering the intricacies of each technology used. Practical recommendations for the execution of connections during the experiment will be included to ensure structural stability. Valuable input from researchers and practitioners regarding both existing and new connections will be incorporated into the experiment's framework.
6. The final step, seismic evaluation, delves into the investigation of seismic effects on connections used during new additions to old structures. The analysis of previously used and proposed connections will provide insights into the seismic response of the frame. Sophisticated micro and macro nonlinear models will be employed, considering calibrated characteristics and hysteretic parameters, to accurately simulate connection behavior. This phase aims to gain essential knowledge about modifications in ductility and energy dissipation capacity within the structural system resulting from the application of proposed connection types. The seismic sustainability capacities of connections will be assessed, drawing appropriate conclusions for both used and proposed connections.

5. Research progress

The current activities are focusing on the last stages of the experimental campaign. The experimental frames were developed to represent the characteristics of a commercial building made of reinforced concrete, with a single span in the global X direction, and several spans in the global Y direction. First, a single span two-story RC frame was cast-in-site to represent an "old" (base) building with monolithic column-beam connections, and then, after several days, an additional frame of one story was added. The connection between the two-story base frame and its vertical extension with an additional single-story frame was made with anchoring executed by first opening the holes in the base structure and then placing the reinforcement bars as anchors and securing them using cement-based adhesive material. Both the two-story model representing the old i.e. base building, and the three-story model representing the vertically extended building are tested. The experimental model was designed as a frame with strong columns and weak beams to meet the ductility conditions of the structure as best as possible.

The quasi-static testing method is used for testing under seismic load action. The experiment needs to provide the results for the tested models for ductility, displacements, capacity, and stiffness of separate elements but also as a whole of the experimental model. Previously, testing of samples to obtain different characteristics of materials used in the experimental model was carried out. Figs. 1 a) and b) illustrate various specimens used to experimentally determine different materials' characteristics, while c) and d) show scaled frame models and quasi-static testing one of the frames in the laboratory.

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Figure 1. a) Samples for testing different characteristics of the materials; b) pull out of anchors under tensile testing; c) Scaled two- and three-story RC frame models; d) Quasi-stating testing one of the frame models.

6. Conclusion

As vertical extensions of buildings are becoming more attractive solutions with some clear advantages in urban spaces, research was launched into investigating the dynamic (seismic) behavior of such buildings as this might be an important, even decisive design and execution criterion in seismically active regions. The research was narrowed to the building typology that is very common in the region in which both the base (old) structure and the vertical extension (added floor) are RC frame structures. The research is aimed at determining the stiffness coefficient of the joint that connects the added floor to the existing base structure. This would lead to refinement of advanced numerical modelling techniques for more precise simulation of column-beam connection joints in such structures, which in turn might serve as a valuable model for future practical applications. The research is also expected to further knowledge of internal forces in the column-beam corner frame joint, thus providing input to

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develop improvements in joint design, detailing and execution as well as global design of vertically extended buildings. The testing of scaled non-extended and extended RC frames is currently underway and the completion of the research is expected in 2025 with subsequent publication of its results.

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