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Experimental and Numerical Analysis of Traditional Column Connections with the Possible Retrofit Concept

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Abstract Several historical constructions in Croatia have permanent column problems, particularly at connections with capitals and bases, characterized by specific fractures. Experimental and numerical analysis of traditional column connections were conducted. Distinct fractures concentrated around the connections, as well as the traces of previous restorations noted by the chronicles, intrigued us to conduct research of the possible fundamental deficiency of the structural system. Traditional connections can be described as carefully smoothed stone contact areas, joined with centrally placed iron dowel fixed with a lead infill in a slightly larger hole. The comprehensive numerical and experimental efforts have shown that even a small imperfection in the construction process or a disturbance of bearing system have consequence, the contact leans to one side. As the joint has a very limited ability to compensate rotations, the relative rotation between column elements causes high local stresses at the edge of a column, which eventually results in numerous fractures. Ignoring or not fully appreciating the real nature of connections leads to significantly different stress distributions and orientations of thrust lines which may grossly overestimate the safety factor. This usually leads to inadequate rehabilitation, but also if no action is taken continuous fracture propagation can endanger local or global stability of the structure. Laboratory tests were performed on stone samples provided from traditional quarries and we tried to restore a rather similar level of stress and stress distribution caused by eccentric forces. Although some results will be presented, final objective will be to obtain the value of rotational stiffness and stress – strain diagram for connections, which is crucial for understanding of the load carrying mechanism, numerical treatment of connections and adequate retrofit strategies. In order to ensure serviceability and durability, we have started to test the possible retrofit concept with a layer of lead placed between two connected areas. The material such as lead enables small rotations and protects connected areas from large stress concentrations. Lead has already been used to fill the dowel holes and the additional horizontal thin layer appears to be an appropriate and almost invisible intervention.

Keywords: Experimental analysis, numerical analysis, stone column, capital, base, column connection, dowel, contact stress, lead

Figure 1: Column connection with specific fractures

Introduction

We have found problems in column connections in the course of rehabilitation project of Rector's Palace in Dubrovnik (Lazarević, Dvornik and Fresl 2004), as have some other authors (Lokošek and Kleiner 2004, Uglešić and Banić 2006) in Croatia. Many examined structures have specific vestiges of previous reconstructions like stirrups around columns, stone insets and gaps filled with lead or wood, broken parts, different types of stones, various styles of column shapes and capitals (Fig. 1). If we also consider numerous distinct found fractures concentrated around capitals and bases the conclusion is that we are dealing with a serious problem in time. Maybe the essence of problem can be described by quoting one historical report (Steinman 1974): *"Damages of particular parts of columns seem to represent a continuous phenomenon which required unusually large number of interventions*". This was motive to make detailed research of traditionally made column and column connections.

Column Connections

Good stonemasons made columns, capitals and bases of high quality stone and with great care. Contact areas are carefully smoothed and joined with iron dowels, centrically placed in a slightly larger hole and finally filled with lead. Such precise finishing is well suited for transmission of vertical load with rather uniform compression stresses, what is beneficial for traditional materials. Unfortunately our experience showed that uniform compression stresses at contact areas is very rare. The thrust lines from vertical loads in columns are inclined and this phenomenon is additionally amplified by imperfections from the construction process, events throughout history like earthquakes, settlements (Meli and Sanches-Ramirez 1997), temperature changes and different rehabilitations. It is almost usual that connections are eccentrically loaded or at least slightly moved from original position. Unfortunately the joint is not designed to compensate such deviations because it can transmit only small bending moments. The rotational stiffness is very small due to insufficient dowel anchoring (about 10 cm) and the lack of adhesiveness amplified by the influence of weak mechanical properties of lead (Fig. 2a). The dowel is centrically placed and hence the internal forces couple negligible and it can transmit only small tensile forces.

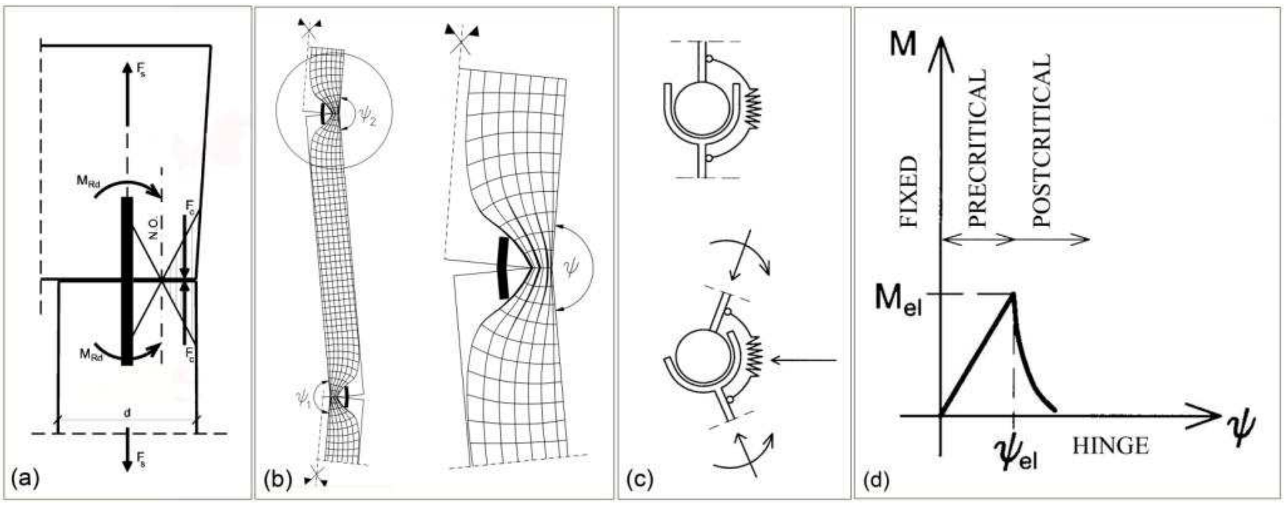

Figure 2: Contact behaviour: (a) rotational capacity, (b) stress trajectories, (c) contact model, (d) approximate $M - \psi$ diagram of contact

The eccentric load causes relative rotation of column elements and because the joint has only a very limited ability to compensate rotations this results in high local stresses at the edge of a column. When stress concentration exceeds the compression strength of stone or the deviation of compression trajectories (Fig. 2b) unwanted tensile forces are generated, which can easily exceed the small tensile strength of stone and cause a column to split. Eventually, this leads to fractures near contact surfaces, splitting of columns and capitals and thereby to a complete loss of bending stiffness or at least to its very significant reduction. It should be noted that the problem is very local in nature as outside of region of approximately 3d from the joint, the trajectories become parallel again (Fig. 2b). Consequently, the body of the column experiences only moderate uniform compression stress and a large safety factor is maintained. Finally, even in fractured state the connection is still capable of transmitting compressive and shear forces and therefore can be idealised as a hinge. But a hinge is always very questionable description, which has been verified by detailed numerical analyses and therefore we have modelled the contact like a hinge with added rotational spring with small stiffness (Fig. 2c). Pre-critical and post-critical behaviour of this spring or springs is one of the main goals of this research (Fig. 2d).

Numerical Modelling Strategies

A variety of numerical models were created to support the above statements: from simple frame and shell models to complex 3D solid models, but also including *traditional* calculations of thrust lines. An extensive parametric approach is needed because large discrepancies in results and lack of solid parameters, as always in historical constructions, may lead only to a qualitative description of the phenomenon.

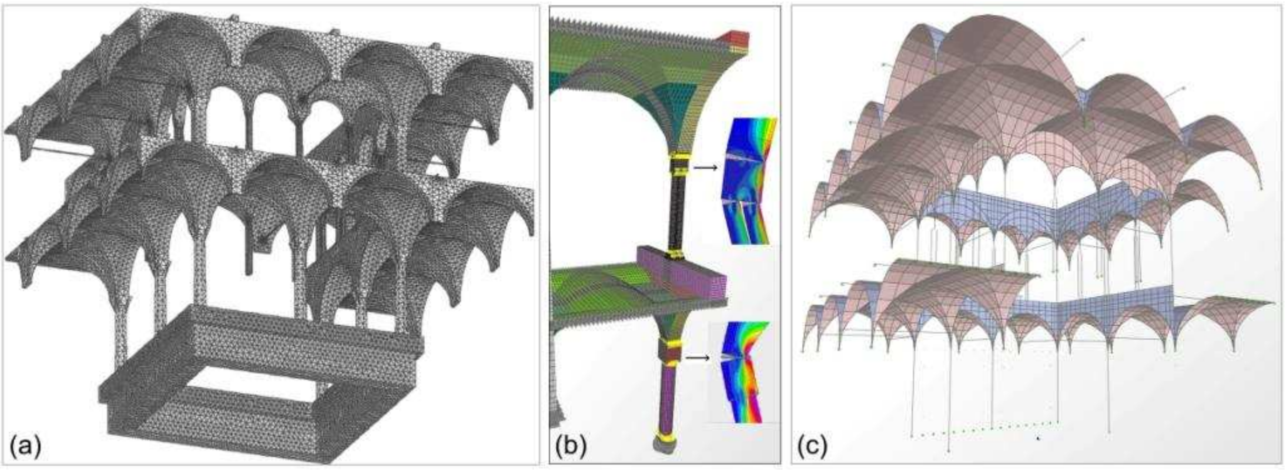

Figure 3: *Numerical models: (a) structure with solid elements, (b) specific part of structure with solid element (c) structure with frame and shell elements*

Model of Structure with Solid Elements (Fig. 3a) In the computational model of complete structure of the Rector's Palace (Lazarević, Dvornik, Fresl and Rak 2006, Lazarević, Atalić and Fresl 2009) we were confronted with the dilemma how to model column contacts with the rest of structure. The model was made with tetrahedral finite elements using FEAP 7.4 (Taylor 2001) combined with GiD 6.1.2a (CIMNE 2000) for pre- and post- processing purposes. Several novel subroutines were implemented into the basic linear elastic FEAP model, to better describe the connection behaviour. The program code was extended to exclude overstressed finite elements and to search the minimal energy in given direction (line search) using the bisection method to improve the convergence of the incremental Newton – Raphson technique. Failure criterion of material was defined by the modified theory of normal stresses, which was originally developed by Galileo and Rankine. Nevertheless, adequate connection behaviour in global model is hard to describe and model is highly impractical for common use. Exclusions of the overstressed elements makes model highly sensitive to input data, so we were focused on more detailed model of connection to closely test connection parameters.

Solid Model of the Characteristic Part of Structure (Fig. 3b) The detailed model of the column connections was performed with SAP2000 (CSI 2002) using brick elements with incompatible modes and 'links' (gaps) elements, which are able to exclude tension stresses**.** Fractures in the vault bearing system were ignored and links were used only at column connections including properties of lead (solid) and the dowel (frame). Even this simple approach was sufficient to obtain sensitivity of contact rotations and overstressing at the edges. The behaviour and positions of overstressed elements matched fairly well with observed fractures, but some parameters like rotational stiffness, post-critical behaviour or position of main fractures were not determined. Hence, the calibration of numerical model with experimental findings appears to be crucial.

Model of Structure with Frame and Shell Elements (Fig. 3c) A mixed frame and shell model of the complete structure was made to study the influence of varying rotational stiffness. Columns were modelled with frame elements and nonlinear rotational stiffness between them was included in the form of a rotational spring. This approach provides insight into the stability problem and the evaluation of the global safety factor, but it is highly sensitive to the changes on local contact properties. Another important benefit was the evaluation of maximal angles of rotations at joints, which identified the size of required dilatation, needed for the connections repair.

Models of various complexities were explored and all of them confirmed the importance and the need for the proper assessment of the column connections. Even everyday temperature gradient or moving load causes both increase as well as decrease of the compression zone and the corresponding changes of splitting forces directly influence opening and closing of cracks. Therefore there is constant activity within these connections and the associated propagation of fractures. Eventually, most of connections are seriously cracked and the bearing capacity is almost exhausted. The structure does not have bearing capacity reserves and the overstressed joints cannot effectively unload. Only three hinges on the characteristic vertical line are sufficient to render the system unstable (Atalić, Lazarević and Fresl 2008). It is hard to devise a unique procedure for the contact analysis s because there are various types of columns, joints and structural systems, but we will try to come close to real behaviour and subsequently calibrate our models.

Description of Experiment

Only a crude behaviour of contacts may be obtained by numerical models and better design parameters for the rehabilitation process are imperative and can only be provided by laboratory tests. Due to Rectors Palace project, specimens from the traditional quarry *Vrnik* were obtained. However, the quarry on *Vrnik* Island is officially closed and only few specimens could be obtained. Therefore, additional samples were acquired from a rather close quarry on island Korčula. To compare two different types of stone and to calibrate our numerical models, results from testing of strength, modulus of elasticity and fracture mechanics parameters were used. Results revealed that stone form Korčula quarry have much larger strength and higher modulus of elasticity, but is less ductile, which makes it more difficult to capture the post-critical contact behaviour. During the tests, specimens usually failed with barely visible fractures, which is contrary to the behaviour of real structures.

Test Setting Originally planned arc and vault system for load implementation was discarded due to the laboratory limitations. We have used the available height to keep column dimensions close to real situation, which is very important for the determination of connection behaviour and fracture propagation. A circular column (d=250 mm, h=1500 mm) was connected with the base (d=300 mm, h=200 mm) and the capital (d=300 mm, h=500 mm) with centrically placed iron dowel without fixing with lead. Cross sections were simplified, without décor/ornaments, but with carefully finished contact areas. Loads were implemented by horizontally placed steel beam which was adapted for two hydraulic pistons, centrically (above column) and eccentrically (at midspan of steel beam). A steel beam (Fig. 4a) was fixed to capital with four anchors on one side and to auxiliary structure with free rotations and fixed horizontal movement on the other (l=2400 mm).

Testing Phases In the first phase of experiment a centric force equal to about 5% of the column strength was implemented. This force value was used to maintain rather normal level of compression stress and together with the load from the second phase closely represented the force, calculated in previously developed numerical models. In the second phase, a force with displacement control at beam midspan was applied, generating beam deformation and consequently rotation of capital. The deformation of beam is very small but enough to cause leaning to one side of column contact. The level of eccentrically placed force was increased until the specimen became fully fractured and lost stability (Fig. 4c). With Linear Variable Differential Transformers (LVDT) sensors of different sensitivity displacements along whole specimen were measured and also deformations at the top, at the middle and at the bottom of column (Fig. 4a). The focus was on rotation of steel beam above capital which was compared and controlled with measured rotation of capital needed for calculation of rotational stiffness. The procedure was calibrated on three concrete (cheaper) specimens (C50/55 without bars), but the behaviour was significantly different related to stone specimens of similar strength.

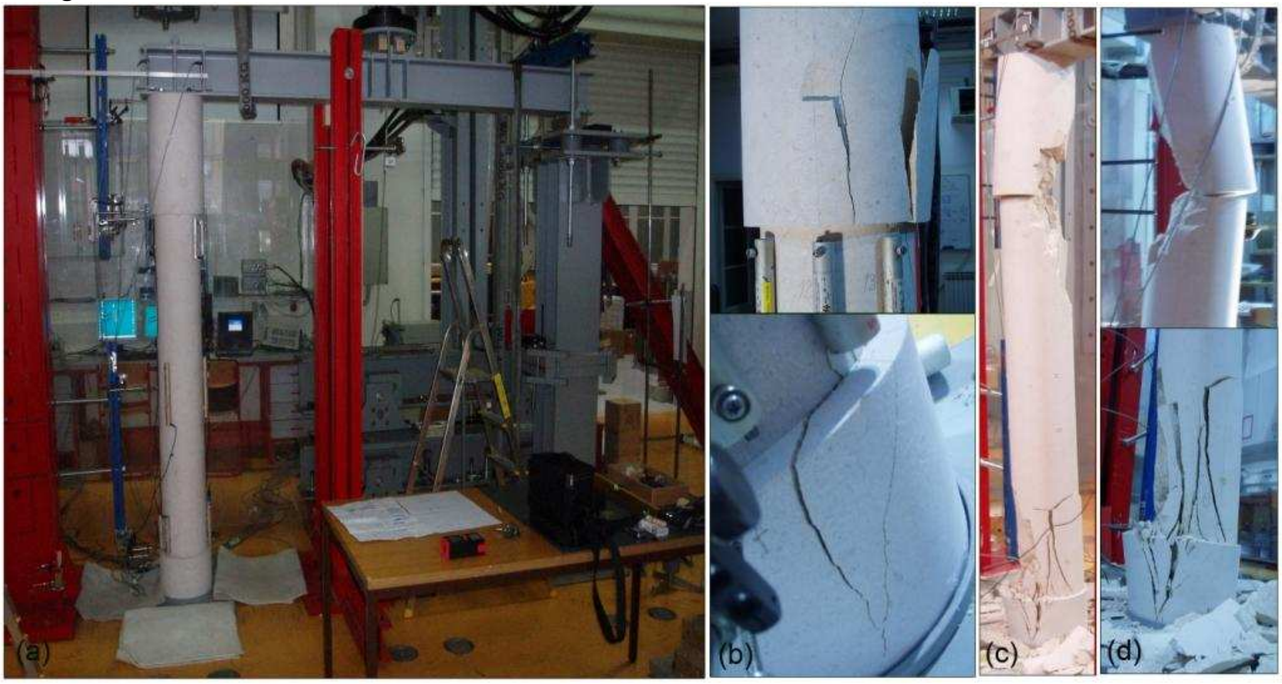

Figure 4: Experiment: (a) test setting, (b) fractures at low level of eccentrically placed force, (c), (d) fractures at the end of testing

We have presented the behaviour of one column made of stone from Korčula which includes most of interesting issues. Even in the first phase of experiment we had a problem how to apply an ideal centric force (450 kN). Laboratory conditions, precisely made and erected elements (distances measured with laser) and careful orientation of piston were not enough to obtain rather similar uniform compression stresses in LVTD-s. This difficulty indicates uncommon sensitivity to imperfections and we can only imagine how many problems old masters had on real construction scene of that time. During loading we could follow the adaption of the column elements, sometimes with visible fractures. In the second phase of experiment eccentrically placed force caused rotation of connected elements and complete leaning to one side of contact. Even at a small force level of 40 kN, fractures appeared around connected elements (Fig. 4b). An additional increase of force to 150 kN caused propagation of fractures and eventually the, specimen collapsed (Fig. 4c, Fig. 4d). Valid results were difficult to obtain in the post-critical region, because values measured by LVDT in fractured state of column are questionable (column parts splintered in the region of LVDT). Here, we are not able to display all results, but with no doubt high sensitivity of contacts to imperfections or any load change can be noticed. Observed fractures (Fig. 4c) fairly match assumed trajectories (Fig. 2b) and numerical results (Fig. 3b) and hence we believe our work to be perfectly adequate.

Additional Tests Several more tests are planned, especially the one with a thin layer of lead between contact areas, which is one of the retrofit strategies. The material such as lead will enable small rotations and will shield connected areas from large stress concentrations. Testing is not finished but preliminary investigations showed that a layer of lead of about 5mm placed between the two connected areas can preserve contact areas from large stress concentration. Lead is already used to fill dowel holes and the additional horizontal thin layer appears as an appropriate and almost invisible intervention. Additionally, stresses due to the pressure of corroded dowels must be included in the analysis, because an increase in the dowel volume and hence local pressure and splitting forces are present and may have substantial influence on the contact problem.

Conclusion

We are convinced that the base and the capital column connections of ancient constructions are mostly in a dangerous post-critical state, due to imperfections from the construction process, events throughout history like earthquakes, differential support settlements, explosions, temperature changes or fires, previous reconstructions and many unknown interventions. All attained results at this investigation phase point to high sensitivity of contacts to disturbance of the structural system or any load change, because state of equilibrium is maintained only by the a small rotational stiffness, in most cases, of cracked stone. The importance of correct analysis must be clearly emphasized, along with the complexities and difficulties associated with such a process. Ignoring or not fully appreciating the real nature of connections leads to significantly different stress distributions and orientations of thrust lines which may grossly overestimate the safety factor. Moreover, the propagation of fractures near the column connections can easily endanger the global stability of structure. Extensive numerical and experimental effort was and will be made to assess better the real behaviour of contacts and to provide more realistic parameters needed for adequate analyses and retrofit strategies.

References

[1] Atalić, J, Lazarević, D, and Fresl, K (2008). "Influence of Rotational Stiffness between Column Elements on Global Stability of Historical Constructions," in *Proc. of the 8th European Conference on Research for Protection, Conservation and Enhancement of Cultural Heritage,* 60-62.

[2] *FEAP – A Finite Element Analysis Program, Version 7.3, Programmer Manual*, University of California, 2001.

[3] *GiD, The universal, adaptive and user friendly pre and post processing system for computer analysis in science and engineering, Reference Manual Version 6,* CIMNE, 2000.

[4] Gubane, A, and Giuriania, E (2004). "Structural restoration of vaults with extrados ties," in *Int. Sem. Structural Analysis of Historical Constructions IV. Possibilities of numerical and experimental techniques,* 745-752.

[5] Lazarević, D, Atalić, J and Fresl, K (2009). "Reconstruction of Rector's Palace Atrium in Dubrovnik: a key role of column connections," in *Structural Studies, Repairs and Maintenance of Heritage Architecture XI,* 289-303.

[6] Lazarević, D, Dvornik, J, and Fresl, K (2004). "Analysis of damages to the Rector's Palace Atrium in Dubrovnik." *Građevinar*, 56(10), 601-612. (in Croatian).

[7] Lazarević, D, Dvornik, J, Fresl, K and Rak, M (2006). "Numerical analysis of damages of the Rectors's Palace atrium in Dubrovnik," in *Proc. of the Int. Conference Heritage Protection - Construction Aspects*, 109-116.

[8] Lokošek, E, and Kleiner, I (2004). "Replacement of stone columns at the ground floor of the Veliki Tabor Castle." *Građevinar*, 56(5), 267-276. (in Croatian).

[9] Meli, R, and Sanchez-Ramirez, A R (1997). "Structural aspects of the rehabilitation of the Mexico City Cathedral," in *Int. Sem. Structural Analysis of Historical Constructions. Possibilities of numerical and experimental techniques*, 123-140.

[10] *SAP2000, Integrated Software for Structural Analysis and Design, Analysis reference manual,* CSI: Berkeley, 2002.

[11] Steinman, V (1974). "Research work on Rector's Palace in Dubrovnik with basic recommendations for reconstruction, Book II," Civil Engineering Institute of Croatia: Zagreb, 50-83. (in Croatian).

[12] Theodossopoulos, D (2008). "Structural design of high gothic vaulting systems in England." *International Journal of Architectural Heritage*, 2(1), 1-24.

[13] Uglešić, D, and Banić, Ž (2006). "Franciscan Monastery St. Frances in Zadar: Structural repair of cloister vault," in *Proc. of the Int. Conference Heritage Protection - Construction Aspects*, 411-418.