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# ANALYSIS OF METAL CONNECTOR'S EFFECT ON SEISMIC RESISTANCE OF DRY STONE MASONRY STRUCTURES

**Željana Nikolić[1]*, Hrvoje Smoljanović[1], and Nikolina Živaljić[1]**

[1] Faculty of Civil Engineering, Architecture and Geodesy
University of Split
Matice hrvatske 15, 21000 Split
Croatia
e-mail: {zeljana.nikolic; hrvoje.smoljanovic; nikolina.zivaljic}@gradst.hr

## Abstract

*In this work, numerical investigations of the behaviour of dry stone masonry structures, reinforced with metal connectors (clamps and dowels), were performed by the finite-discrete element model for strengthened dry-stone masonry structures. The geometrical and material model of the metal connectors were developed and implemented into the finite-discrete element model in order to analyse the influence of the connectors to strengthening capacity of the structure. The yielding and extracting of the connectors (clamps and dowels) from the holes were represented by experimental force-displacement curves, obtained by testing the samples composed of two stone blocks connected with clamps or dowels. An incremental dynamic analysis up to the structural failure was applied in order to determine failure mechanisms and collapse load. The results were compared to those obtained for unreinforced structures. The results show the performance of the applied model in simulation of the behaviour of historical monuments, composed of stone blocks with dry joints and connectors, in the dynamic regime. The model is complex and time consuming, but it can be useful for making decisions related to reconstruction and increasing the earthquake resistance of the historical buildings.*

**Keywords:** Dry-stone masonry structures, Metal connectors, Seismic resistance, Finite-discrete element method.

## 1 INTRODUCTION

A commonly used method for increasing seismic resistance of historical dry-stone masonry structures is strengthening with different types of metal connectors. The connectors (clamps and dowels) are embedded into the previously made holes in stone blocks that are subsequently backfilled with infill material like lead. Clamps are used in order to increase tension bearing capacity of dry stone arches, while dowels are used for connecting the capitals and columns or capitals and upper beams and they dominantly influence to shear bearing capacity. Representative examples of strengthened stone masonry structures are Protiron monument in Split, Croatia and Old Bridge in Mostar, Bosna and Hercegovina [1].

Computational analysis of the behaviour of these structures under the earthquake and their seismic resistance is demanded due to discontinuous nature and coupling of the different materials in a composite unit. Applied numerical model could take into account all effects occurring in dry stone masonry structures including the fragmentation of the blocks and non-linear behavior of clamps and dowels during dynamic loading. Many parameters influence on the behavior of clamps and dowels, such as material properties of stone and connectors, the geometry of the hole (width and depth), material properties of infill material, geometry of connectors as well as stone-infill and infill-connector interaction. Detail analysis of all mentioned effects, which can take into account different types of failure mechanisms and especially the influence of local interaction between the dowels or clamps on one side and stone block on another, leads to micro-modelling approach which is not suitable for analysis of the whole structure. Another approach, presented in this paper, is modelling of the effects of strengthening through the integral approach considering material properties, geometrical properties and effects of the connectors and infill through the united force-displacement law.

A basis of our numerical model is finite-discrete element method which offered the framework for simulation of the main discontinuity effects in the dry-stone masonry structures such us sliding of the stone blocks and their fracture and fragmentation [2, 3]. Few years ago our team developed 2D numerical model for dry-stone masonry structures with embedded dowels and clamps [4]. The model is based on finite-discrete element method and can simulate movement of the stone blocks, their fracture and fragmentation, yielding and extracting of the clamps and dowels and failure of the structure. The model was also extended to 3D problem [5]. Modelling of the steel material was performed for monotonic and cyclic loading, where the energy dissipation due to the cyclic behavior of a steel is enforced through Kato's stress-strain model [5]. Moving of the stone blocks causes extraction of the clamps and dowels from the holes due to the tangential and shear separation, leading to the reduction of the normal stress in the clamps and shear stress in the dowels. Reduction of the stress is a result of complex behavior and interaction between different materials in the holes. In our previous investigations it was modelled through the scaling function taken from literature [6], which were not experimentally validated on the strengthened stone masonry structures.

In this paper the main features of finite-discrete element model for dry stone masonry structures strengthened by connectors was firstly introduced. The effects of strengthening was modelled through integral force-displacement curves, obtained by experimental investigations [7]. An incremental dynamic analysis up to the structural failure was applied in order to determine failure mechanisms and collapse load for Prothyron monument [1]. The results for unstrengthen and strengthened structure were compared in order to present influence of the connectors to seismic resistance of these structures.

## 2 FINITE-DISCRETE ELEMENT MODEL FOR STRENGTHENED DRY STONE MASONRY STRUCTURES

Stone block in dry stone masonry structure is modelled as a discrete element which can be discretized by 2D triangular or 3D tetrahedron finite elements. Contact interaction between stone blocks is considered through the contact interaction algorithm based on the principle of potential contact forces [8]. Material non-linearity, fracture and fragmentation are considered through the contact elements which are placed within the finite element mesh of each block.

The clamps and dowels were modelled with one-dimensional elements embedded in the stone finite elements. Discretization of dry stone masonry structure with clamps and dowels is shown in Figure 1. More details about model can be found in the literature [2-5].

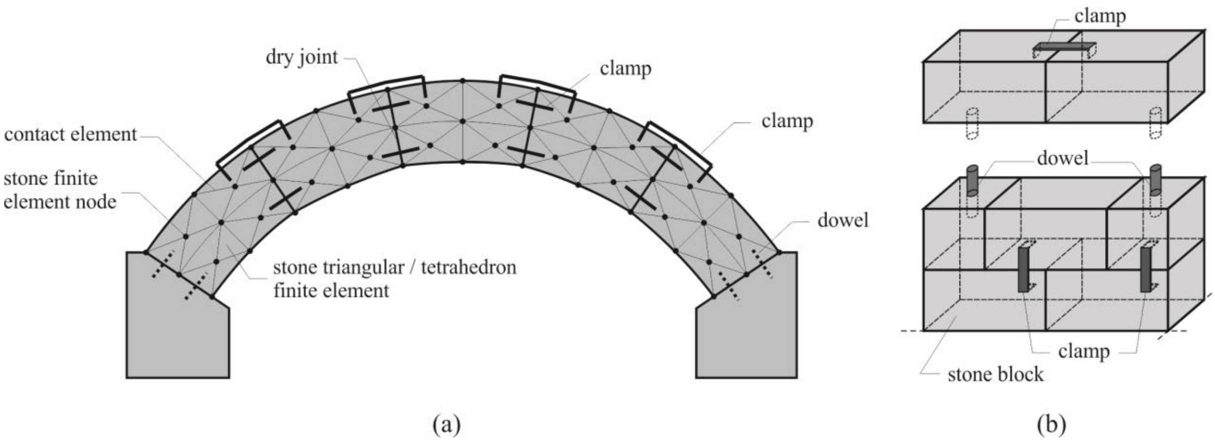



Figure 1: Discretization of dry stone structure with embedded connectors (clamps and dowels): (a) whole structures; (b) position of the connectors

## 3 MODELLING OF THE INFLUENCE OF CONNECTORS TO STONE BLOCKS

The effects of strengthening achieved by clamps and dowels, embedded into the holes in stone blocks, was experimentally investigated through the samples of two stone blocks connected with clamp or dowel and subjected to tensile and shear forces which produced pull-out of the clamp and dowel [7], Figure 2.

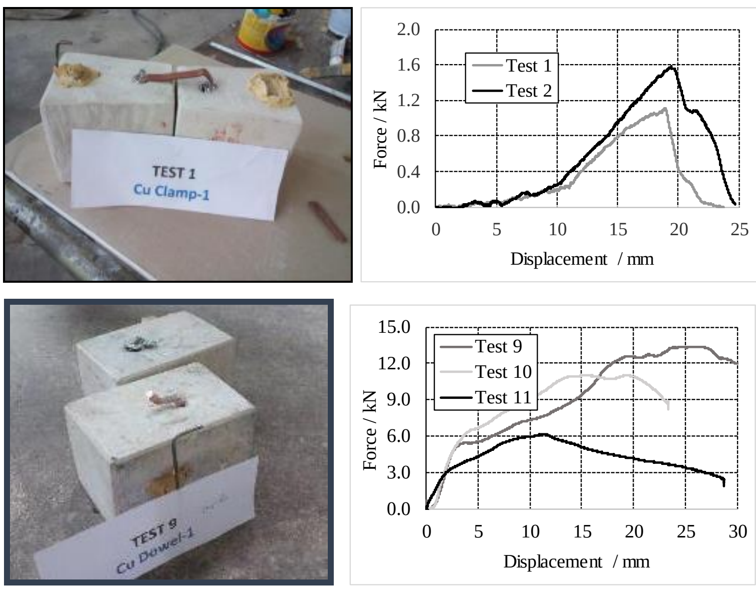
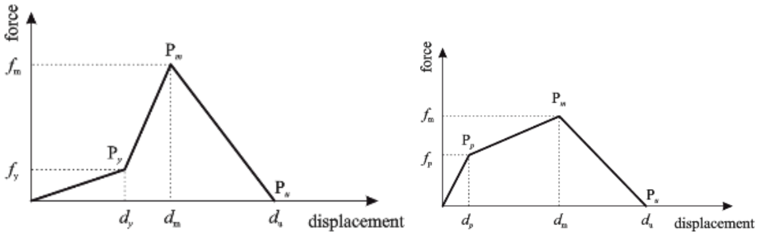



Figure 2: Pull-out of the clamp and the dowel with corresponding force-displacement curves

The material and geometrical characteristic of the clamp, dowel, infill and holes corresponded to those in Protiron monument [1]. Force-displacement curves obtained from experiments are used to model coupled behaviour of the dry stone blocks with clamps and bolts which enable the estimation of the seismic resistance of the structure at macro-level. Figure 2 shows the samples of clamp and dowel with accompanied force-displacement laws. The models of the clamp and the dowel, implemented in analysis, are presented in Figure 3. Characteristic values in the model are yielding/pulling-out forces $f_y$, $f_p$ in the clamp and dowell and corresponding displacement $d_y$ and $d_p$, maximum force $f_m$ and corresponding displacement $d_m$, and ultimate displacement $d_u$.




(a) Clamp (b) Dowel

Figure 3: Models of the clamp and the dowel

## 4 NUMERICAL ANALYSIS OF HISTORICAL STRUCTURE

The influence of the effect of connectors was analysed on the ancient historical structure Prothyron, located in Split in Croatia. The structure consists of columns, capitals and broad gable. It was originally built of dry stone blocks with dowels embedded between columns, capitals and the upper beams. Due to the movement of the blocks in the broad gable, restoration of the structure was performed by clamps at the beginning of the 20$^{th}$ century.

The incremental dynamic analysis of structural response, based on finite-discrete element method was performed for two cases, original structure before restoration with dowels between columns, capitals and the upper beams, and the structure after restoration where the broad gable strengthened with copper clamps. The structure was exposed to horizontal ground acceleration represented by Petrovac (Montenegro) earthquake, recorded on 15.4.1979. The applied accelelogram gradually increased, starting with peak ground acceleration $a_g$=0.22 g which is valid for Split, up to the collapse of the structure.

Figure 5 shows geometry of the structure with position of the clamps and dowels.

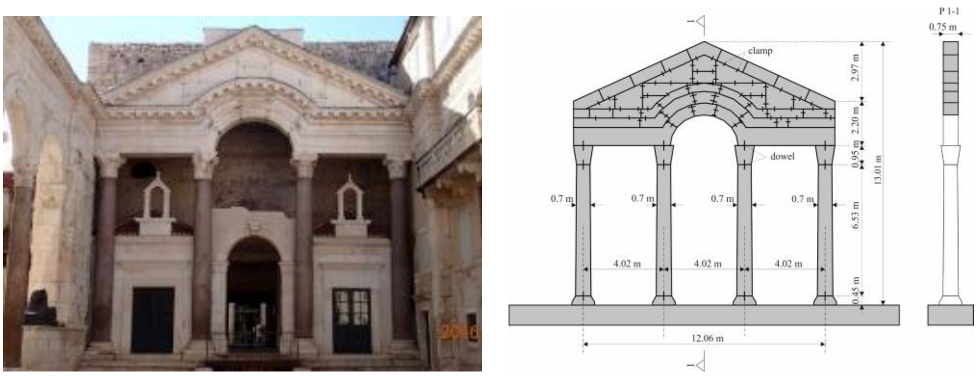
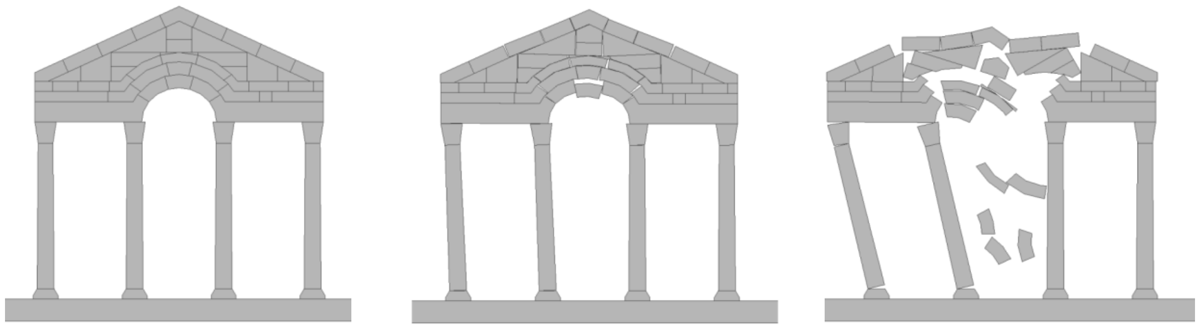



Figure 5: Prothyron structure: view, dimensions, position of clamps and dowels

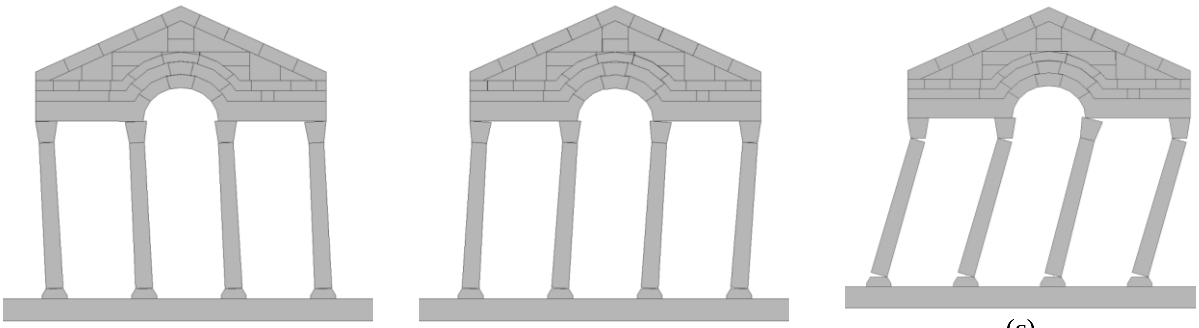
Dowels were made of steel with tensile strength of 414 MPa, shear strength of 239 MPa and modulus of elasticity of 181000 MPa. Cooper clamps have tensile strength and modulus of elasticity 125 MPa and 65000 MPa, respectively. Material characteristics of the stone are compressive strength 100 MPa and tensile strength 10 MPa. Stone fracture energy was assumed as 720 N/m in tension and 1440 N/m in shear.

Effect of strengthening was examined on simplified 2D model where the real boundary conditions were neglected and both clamps and dowels were made of cooper. Dynamic analysis showed that the collapse of dry stone structure with bolts occurred for the acceleration of $a_g$=0.60g (Figure 6) due to the significant movement of the blocks in the broad gable which caused moving of the central columns and complete structural failure. The strengthening of the broad gable by the clamps caused significant higher collapse acceleration ($a_g$=2.0g), see Figure 7.



(a) (b) (c)

Figure 6: Collapse mechanism of the structure with dowels for $a_g$=0.60g: (a) t=0.0 s; (c) t=15.5 s; (f) t=20.4 s



(a) (b) (c)

Figure 7: Collapse mechanism of the structure with dowels and clamps for $a_g$=2.0g: (a) t=6.4 s; (b) t=18.0 s; (c) t=22.0 s

## 5 CONCLUSIONS

- The collapse of the structure with dowels is result of the opening of the contacts between the stone blocks in the broad gable which caused moving of the central columns and final structural failure. The collapse occurred for acceleration 0.60g.
- Structure with dowels and clamps have shown quite different behavior. Namely, clamps between the stone blocks of the broad gable controlled the movement of the blocks. Dowels held the connections of the columns with bases, capitals and horizontal beams. The collapse occurred due to the reaching critical opening of the contacts at the ends of the columns and losses of geometrical stability when the large mass broad gable, moved to one side causing complete loss of connections with the columns. The collapse acceleration was 2.0g.

- Comparative analysis of the structures with and without clamps have shown that the strengthening of dry stone masonry structure can completely change the collapse mechanism and result with significant higher collapse acceleration.
- Numerical model presented in this paper can use in analysis of the failure mechanisms and failure load in dry stone masonry structures subjected to the earthquakes. The model is complex and time consuming, but it can be useful for making decisions related to reconstruction and increasing the earthquake resistance of the historical buildings.

## ACKNOWLEDGEMENTS

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