ANALYSIS OF CRACKS AT THE CONTACT OF REINFORCED CONCRETE AND STONE WALLS OF KANLI KULA

Damir Jagodić [1], Smilja Bursać [2*]

[1]International BURCH University, Sarajevo, Bosnia and Herzegovina
[2]Faculty of Civil Engineering Subotica, University of Novi Sad, Subotica, Serbia
*corresponding author: bursacsmilja@gmail.com

Paper type: Original scientific paper
Received: 2025-07-18
Accepted: 2025-08-20
Published: 2025-09-30

UDK: 624.012.4:519.6
DOI: 10.14415/JFCE-918

ABSTRACT:

Kanli Kula, a historic fortress characterized by the juxtaposition of original stone masonry and later reinforced concrete additions, exhibits significant cracking at the contact zones between these two materials. This study investigates the causes and patterns of cracking at these interfaces through a combination of field surveys, material characterization, and numerical modelling. A detailed literature review provides the theoretical framework for understanding material incompatibility and stress development in composite historic structures. The research methodology includes visual inspection, non-destructive testing, and finite element analysis to simulate stress distribution and crack propagation. Results reveal that differential stiffness, thermal expansion, settlement and moisture movement between the stone and concrete elements are primary contributors to crack formation. The findings emphasize the importance of compatible repair techniques and informed intervention strategies in the conservation of hybrid historic structures. Recommendations are offered for future restoration efforts to ensure the long-term stability and authenticity of Kanli Kula.

KEYWORDS:

Kanli Kula, Cracks, Reinforced-Concrete Walls, Stone Walls, Numerical analysis.

1 INTRODUCTION

Historic structures are invaluable witnesses to the architectural, cultural, and social achievements of past civilizations. Among them, the Kanli Kula fortress in Herceg Novi stands as a prominent monument, reflecting centuries of complex construction techniques, restorations, and adaptations. A significant feature of Kanli Kula is the interface between reinforced concrete additions and original stone masonry walls, a junction that has been subjected to environmental influences, mechanical stresses, and material incompatibilities over time. One of the most critical issues observed at these contact zones is the development and propagation of cracks, which threaten not only the aesthetic value but also the structural integrity of the fortress.

The phenomenon of cracking at the interface between disparate materials such as reinforced concrete and stone masonry has been widely acknowledged in conservation engineering. Differences in mechanical properties—such as stiffness, thermal expansion, and moisture behaviour—can lead to stress concentrations and differential movements that initiate and exacerbate cracking. In the context of historic preservation, understanding the mechanisms behind such damage is essential for planning effective repair strategies that respect the authenticity and durability of the structure.

Figure 1: Front side of the Kanli Kula fortress with visible cracks

This paper presents a detailed analysis of cracks at the contact zones of reinforced concrete and stone walls of Kanli Kula. Following a comprehensive review of relevant literature, the research design and methodology for field inspection, material characterization, and numerical modelling are outlined. Subsequently, numerical analyses are conducted to simulate the structural behaviour of the walls and assess crack formation patterns. Finally, findings are discussed in the broader context of historical conservation, and conclusions are drawn to inform future interventions aimed at preserving the structural and historical value of Kanli Kula in Herceg Novi.

2 LITERATURE REVIEW

The interface between historic masonry and modern reinforced concrete often becomes a focal point of structural vulnerability due to contrasting material properties and construction timelines. Stone masonry, typically used in historic fortifications, behaves differently under load and environmental stress compared to reinforced concrete. Several studies have identified differential stiffness, time-dependent settlement, and inconsistent thermal expansion as key factors contributing to cracking at these junctions [1], [2].

Historic stone masonry walls often undergo long-term creep and settlement, stabilizing gradually over decades or centuries. When new concrete elements are later added without proper transition detailing or accommodation of movement, they impose rigid constraints that lead to localized stress concentrations and eventual cracking [3]. These effects are especially pronounced in areas with active soil movement or seismic influence, where the mismatch in dynamic response becomes even more critical.

Research has emphasized the importance of using flexible or deformable interfaces between the two materials or designing the concrete elements to “float” independently over older structures [4]. When such measures are absent, as is the case in many historic interventions, the result is often early degradation at the interface, visible as both horizontal and vertical cracking.

When heritage structures are located in landslide-prone zones, additional complexity arises due to ground movement, especially in layered or composite structural systems. Differential soil displacement affects various parts of the structure in non-uniform ways, with rigid elements like reinforced concrete reacting differently compared to older, more deformable masonry systems [5].

In such contexts, reinforced concrete often suffers tensile cracking, while the masonry may accommodate deformation through joint opening or compression. This divergence in mechanical behaviour accelerates the deterioration of contact zones between materials. Moreover, inadequate or outdated drainage systems exacerbate pore water pressures, increasing landslide activity and triggering progressive failure patterns in foundations and lower wall segments [6].

The Kanli Kula fortress presents a clear case of these principles. As documented in the conservation and geotechnical reports [7], active terrain deformation has been observed, and the resulting movement impacts the reinforced concrete and stone masonry components differently. The absence of movement joints and incompatible construction phasing have further contributed to the damage patterns currently observed.

The structural integrity of the Kanli Kula fortress is significantly affected by cracks that have developed at the interface between its original stone masonry walls and the more recent reinforced concrete additions. These cracks are not merely surface-level defects but are indicative of deeper incompatibilities between materials and construction periods.

The primary cause of cracking at the contact zones lies in the historical timeline of the fortress’s development. The original stone masonry walls were constructed centuries ago and have since undergone long-term settlement and adaptation to the terrain. In contrast, the reinforced concrete elements were introduced much later, on top of or adjacent to a structure that had already largely completed its consolidation. As a result, the newer concrete walls have been subjected to post-construction differential settlement relative to the pre-existing stone walls, creating tension and stress concentrations precisely at the interface.

Additionally, the entire fortress is situated on an active landslide zone. This introduces ongoing soil movements that affect different structural elements in varying ways. Stone masonry, being massive and somewhat flexible due to its dry or mortar-bound joints, tends to accommodate minor displacements gradually. Reinforced concrete, on the other hand, responds more rigidly and is less forgiving to movement, leading to higher stress accumulation and visible cracking, particularly where it connects to the more compliant stone sections.

In conclusion, the formation of cracks at the contact between the stone masonry and reinforced concrete walls of Kanli Kula is driven by the temporal gap between their construction, the difference in material behaviour, and their distinct responses to continuous terrain displacement.

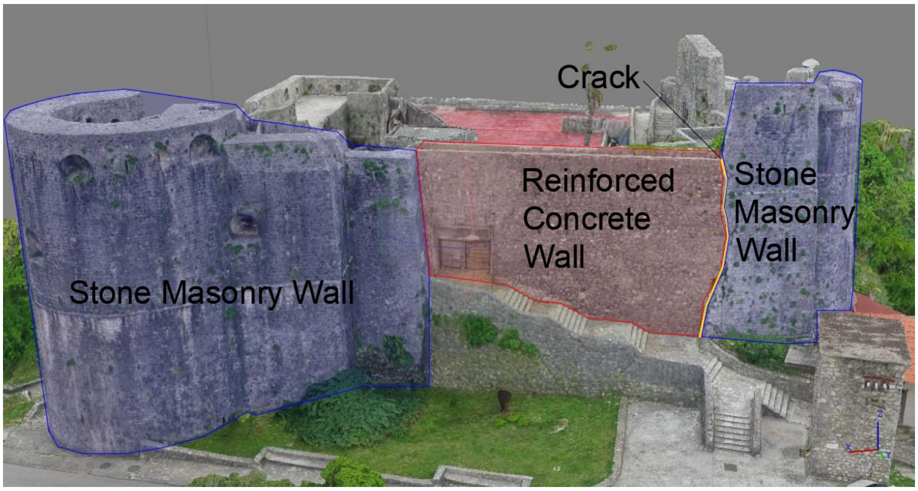

Figure 2: Front side of the Kanli Kula fortress with different structural systems

3 RESEARCH DESIGN AND METHODOLOGY

This research uses a combination of literature review, data analysis, and numerical calculations to address its objectives. The methodology can be broken down into the following key stages:

3.1 DATA COLLECTION AND LITERATURE REVIEW

The initial phase of the research focuses on gathering relevant information and reviewing existing studies to establish a solid theoretical foundation.

A comprehensive review of the Kanli Kula structure was performed. The review focused on:

- Soil geomechanical and structure material parameters.
- Geometrical characteristics of the existing reinforced-concrete and stone masonry walls.

3.2 DATA ANALYSIS AND NUMERICAL MODELLING

Following data collection and literature review, a combination of data analysis and numerical modeling. Numerical modelling was conducted using finite element software to simulate the behaviour of the reinforced concrete and stone masonry walls.

- **Model Development**: Geometric and material properties of the soil and structure were modelled.
- **Validation**: FEA results were validated against measured data to ensure accuracy.
- **Parametric Studies**: The model was used to perform parametric studies on crack width and settlement.

4 NUMERICAL ANALYSIS

To simulate the structural behaviour of the Kanli Kula fortress, a 3D numerical model was developed using Plaxis 3D, a finite element software specialized for geotechnical and soil-structure interaction analysis. The subsurface conditions were modelled using the Hardening Soil (HS) model, which provides a more advanced representation of nonlinear stress-strain behaviour in soils, incorporating both shear and volumetric hardening, as well as stress-dependent stiffness. This enables a more realistic simulation of soil response under loading and deformation. The fortress walls, comprising both historic stone masonry and later reinforced concrete additions, were modelled as linear elastic materials, with distinct stiffness and mechanical properties assigned to each structural type. The critical interface between the stone masonry and the concrete wall was explicitly modelled using contact elements to capture differential displacement, stress transfer, and potential crack initiation along the joint. The model aims to assess the development of stress concentrations and deformation patterns due to differential settlement and continuous soil movement typical of the landslide-prone terrain on which the fortress is located.

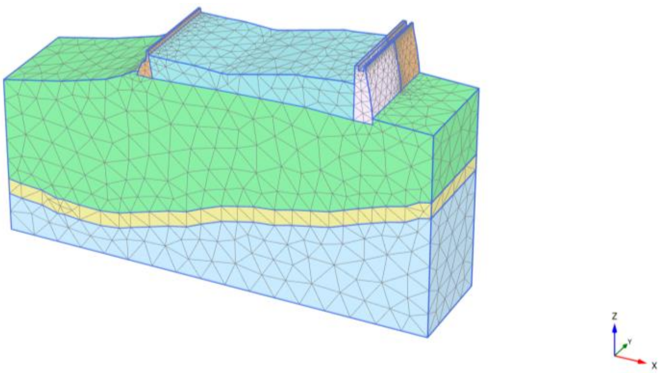

Figure 3: Numerical model in Plaxis 3D

Table 1: Soil layers material properties

Identification		Deluvium	Flysch	Backfill Material	Degraded Flysch	Limestone block
Identification number		2	3	5	6	7
Drainage type		Drained	Drained	Drained	Drained	Drained
Colour						
Comments						
γ_{unsat}	kN/m³	19.00	23.00	19.50	21.00	26.00
γ_{sat}	kN/m³	20.00	24.00	20.00	22.00	26.00
Dilatancy cut-off		No	No	No	No	No
e_{init}		0.5000	0.5000	0.5000	0.5000	0.5000
e_{min}		0.000	0.000	0.000	0.000	0.000
e_{max}		999.0	999.0	999.0	999.0	999.0
Rayleigh α		0.000	0.000	0.000	0.000	0.000
Rayleigh β		0.000	0.000	0.000	0.000	0.000
E_{50}^{ref}	kN/m²	12.00E3	200.0E3	15.00E3	20.00E3	1.000E6
E_{oed}^{ref}	kN/m²	12.00E3	200.0E3	15.00E3	20.00E3	1.000E6
E_{ur}^{ref}	kN/m²	36.00E3	600.0E3	45.00E3	60.00E3	3.000E6
power (m)		0.5000	0.5000	0.5000	0.5000	0.5000
Use alternatives		No	No	No	No	No
C_c		0.02875	1.725E-3	0.02300	0.01725	0.3450E-3
C_s		8.625E-3	0.5175E-3	6.900E-3	5.175E-3	0.1035E-3
Identification		**Deluvium**	**Flysch**	**Backfill Material**	**Degraded Flysch**	**Limestone block**
e_{init}		0.5000	0.5000	0.5000	0.5000	0.5000
c_{ref}	kN/m²	9.000	100.0	1.000	1.000	300.0
φ (phi)	°	31.00	32.00	30.00	15.00	45.00
ψ (psi)	°	1.000	2.000	0.000	0.000	15.00
Set to default values		No	No	No	No	No
ν_{ur}		0.2000	0.2000	0.2000	0.2000	0.2000
p_{ref}	kN/m²	100.0	100.0	100.0	100.0	100.0
K_0^{nc}		0.4300	0.4300	0.4300	0.6300	0.3200
c_{inc}	kN/m²/m	0.000	0.000	0.000	0.000	0.000
z_{ref}	m	0.000	0.000	0.000	0.000	0.000
R_f		0.9000	0.9000	0.9000	0.9000	0.9000
Tension cut-off		Yes	Yes	Yes	Yes	Yes
Tensile strength	kN/m²	0.000	0.000	0.000	0.000	0.000
Undrained behaviour		Standard	Standard	Standard	Standard	Standard
Skempton-B		0.9866	0.9866	0.9866	0.9866	0.9866
ν_u		0.4950	0.4950	0.4950	0.4950	0.4950
$K_{w,ref}$ / n	kN/m²	1.475E6	24.58E6	1.844E6	2.458E6	122.9E6
Stiffness		Standard	Standard	Standard	Standard	Standard
Strength		Rigid	Rigid	Rigid	Rigid	Rigid
R_{inter}		1.000	1.000	1.000	1.000	1.000
Consider gap closure		Yes	Yes	Yes	Yes	Yes
δ_{inter}		0.000	0.000	0.000	0.000	0.000

Table 2: Reinforced concrete and stone wall properties

Identification		Concrete wall	Stone wall
Identification number		1	4
Drainage type		Drained	Drained
Colour			
Comments			
γ_{unsat}	kN/m³	25.00	19.00
γ_{sat}	kN/m³	25.00	19.00
Dilatancy cut-off		No	No
e_{init}		0.5000	0.5000
e_{min}		0.000	0.000
e_{max}		999.0	999.0
Rayleigh α		0.000	0.000
Rayleigh β		0.000	0.000
E	kN/m²	30.00E6	2.310E6
ν (nu)		0.2000	0.2000
G	kN/m²	12.50E6	962.5E3
E_{oed}	kN/m²	33.33E6	2.567E6
V_s	m/s	2215	704.9

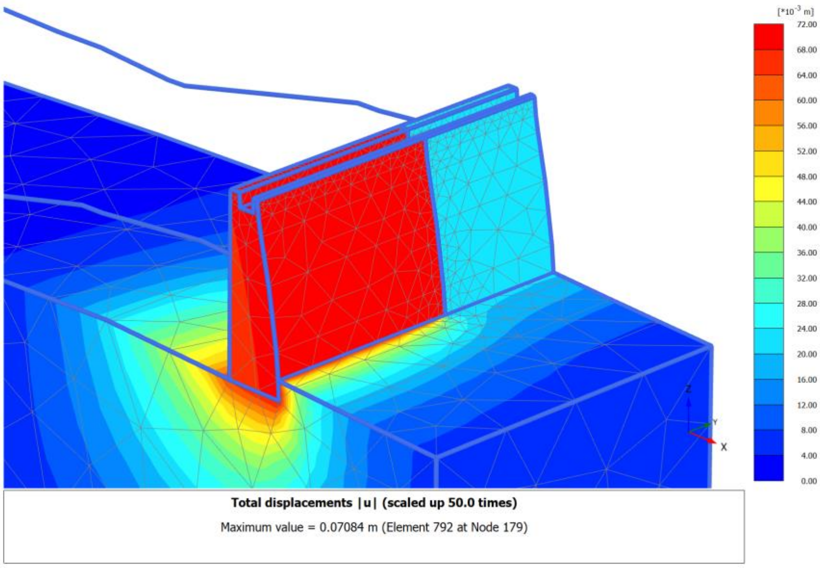

Figure 4: Total displacements in the zone of reinforced concrete and stone masonry wall

The results of the numerical analysis indicate a relative total displacement of approximately 4 cm between the reinforced concrete wall and the adjacent stone masonry wall. This value closely corresponds with in-situ measurements, where the width of the observed crack at the contact zone is approximately 3 cm, validating the accuracy of the model. Additionally, the stress distribution analysis reveals the presence of tensile stresses concentrated along the contact interface between the two materials. These tensile zones, which exceed the tensile strength of the masonry and interface cohesion, are consistent with the mechanism of crack initiation and propagation observed on site.

The combination of differential displacement and localized tension confirms that the structural separation is primarily driven by incompatible deformations and stiffness contrasts between the old and new wall segments.

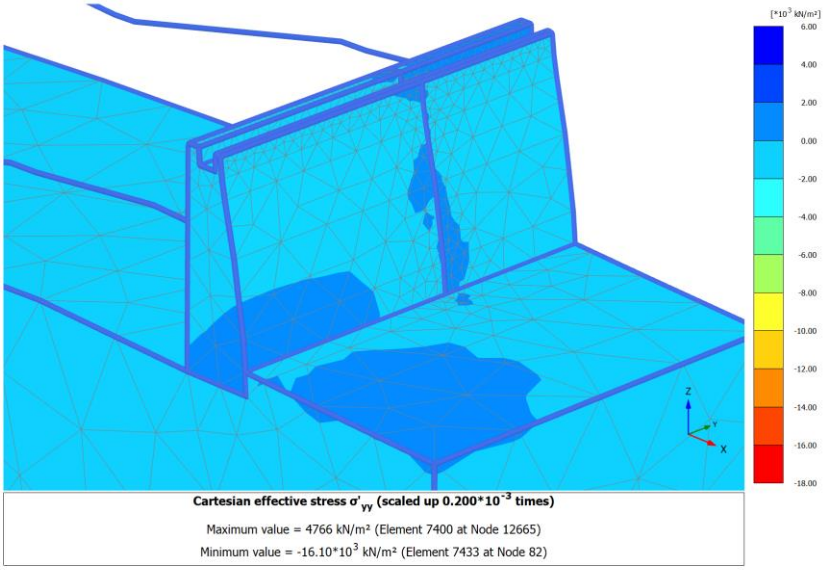

Figure 5: Normal stresses in the zone of reinforced concrete and stone masonry wall

5 DISCUSSION AND CONCLUSION

The results of the numerical analysis clearly demonstrate the structural implications of the material and temporal discontinuity at the interface between the reinforced concrete and stone masonry walls of Kanli Kula. A relative total displacement of approximately 4 cm was observed in the simulation between the two wall types, which closely matches the measured crack width of about 3 cm on site. This agreement validates the model and supports the hypothesis that the cracking at the interface is a consequence of differential settlement and incompatible deformation behaviour between the two structural systems.

The underlying cause of this cracking lies in the construction history of the fortress. The stone masonry walls were built centuries ago and have long since completed their settlement process. In contrast, the reinforced concrete wall was introduced in a much later period, placing a new load on the already-consolidated soil. This caused additional settlement under the concrete wall, while the stone wall remained largely stationary. As a result, the interface between the two materials became a natural weak point, susceptible to stress concentrations and displacement differentials.

Moreover, the mechanical properties of the two materials significantly differ. The reinforced concrete exhibits a higher stiffness and lower tolerance for movement compared to the more deformable, jointed stone masonry. When subjected to ongoing terrain movement caused by active landslide processes, these materials respond differently: the masonry wall adapts slowly through internal joint adjustments, while the concrete wall resists such deformations, resulting in the build-up of tensile stresses along the contact interface. This mismatch is reflected in the stress distribution analysis, which shows that the interface zone is dominated by tensile stresses that exceed the cohesion of the joint and the tensile capacity of the masonry. These findings are in line with previously documented mechanisms in hybrid masonry-concrete systems (e.g., [4], [3].

The identified cracks pose a significant risk to the long-term durability of both the reinforced concrete and the stone masonry walls. If left unaddressed, these cracks can promote moisture ingress, corrosion of reinforcement, and further mechanical degradation, particularly under environmental exposure or seismic loading. Additionally, the presence of cracks weakens the interface bond, leading to progressive separation and potential loss of structural continuity between the wall systems.

To mitigate these risks, several remedial strategies are recommended:

- Injection grouting with flexible, compatible materials to fill cracks and restore contact strength without restricting future minor movements.
- Installation of stainless steel anchors or ties across the interface to improve mechanical linkage and distribute stresses more evenly.
- Introduction of a compressible buffer layer or movement joint, where feasible, to accommodate differential movement in future restorations.
- Improvement of subsurface drainage and stabilization of surrounding soil to reduce further settlement or lateral movement, especially given the fortress's location on a landslide-prone slope.

Overall, the research highlights the importance of considering construction history, material compatibility, and geotechnical context in the preservation of hybrid historic structures. The findings from this study can inform future conservation efforts at Kanli Kula and similar heritage sites facing complex structural and geotechnical challenges.

ACKNOWLEDGEMENTS

The present work has been supported by The Provincial Secretariat for Higher Education and Scientific Research, Autonomous Province of Vojvodina, Republic of Serbia (Project No. 142-451-2640/2021-01).

REFERENCES

[1] G. Magenes and G. M. Calvi, "In-plane seismic response of brick masonry walls," *Earthquake Engineering & Structural Dynamics,* vol. 26, no. 11, p. 1091–1112, 1997.

[2] L. Pelà, M. Cervera and P. Roca, "Continuum damage model for orthotropic materials: Application to masonry," *Computer Methods in Applied Mechanics and Engineering,* vol. 200, no. 9–12, p. 917–930, 2011.

[3] P. B. Lourenço, "Computations on historic masonry structures," *Progress in Structural Engineering and Materials,* vol. 4, no. 3, p. 301–319, 2002.

[4] A. Giordano, E. Mele and A. DeLuca, "Modelling of historical masonry structures: Comparison of different approaches through a case study," *Engineering Structures,* vol. 24, no. 8, p. 1057–1069, 2002.

[5] P. Croce, P. Formichi and L. Landi, "Structural risk assessment of historical buildings," *Journal of Cultural Heritage,* vol. 11, no. 4, p. 539–550, 2010.

[6] M. Cardinali, P. Reichenbach, F. Guzzetti, F. Ardizzone, G. Antonini, M. Galli and M. Cacciano, "A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy," *Natural Hazards and Earth System Sciences,* vol. 2, no. 1/2, p. 57–72, 2000.

[7] Winner-Project, "Sanacija klizišta Kanli Kula – Glavni projekat," Sarajevo, Bosnia and Herzegovina, 2022.