Thiasos - Convegni

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Calculating reinforcement for fragmented architectural members a three dimensional approach

Antigone Vrouva*

Keywords: analysis method, ancient monuments, ancient Greek architecture, Athens; calculation, fractures; fragmented architectonical members; methodology, Parthenon, reinforcement, restoration, simplified theory

Parole chiave: architettura greca, armatura, Atene, calcolo, fratture, elementi architettonici fratturati, metodologia, monumenti antichi, metodo di analisi, Partenone, restauro, teoria semplificata

Abstract

In the Acropolis of Athens restoration project it is very often to come across significant fractures on the architectural marble members. The common practice of the restoration work is to join the marble fragments together with threaded titanium bars, inserted into drilled holes inside the marble and fixed into place with cement mortar. The estimation of the design loads of structures such as the Acropolis monuments is a very difficult task especially when the seismic response is concerned. For this reason elaborate and accurate methods and analytical tools have been used with very good results. At the recent times discrete elements analysis seems to predict accurately enough the response of these structures and provides a time effective method as opposed to the use of finite element analysis. But the use of such methods for calculating the required reinforcement in each fracture is not yet feasible in a large scale, thus simplified methods are still used to facilitate the work on the site.

The methodology of calculating the required reinforcement so far consisted of simplified two dimensional analogies of the fractures and the reinforcement as well as the loading conditions.

This article presents a concise and simplified methodology for the calculation of the required reinforcement for fragmented architectural members taking into account the effects of the three spatial dimensions (geometry of the fracture, geometry of the reinforcement and geometry of the loading). In this approach the problem of calculating the expected tension of the reinforcement in complicated spatial forms of fracture is dealt with. The important features and requirements meant to be kept by this project was that the final product should maintain the character of an easy to use and accessible tool that would respond in real time to facilitate the work of the civil engineers on the site.

Nel progetto di restauro dell'Acropoli di Atene molto spesso ci si imbatte in fratture significative sulle membrature architettoniche in marmo. La pratica comune dei lavori di restauro è quello di unire i frammenti di marmo insieme con barre filettate in titanio, inserite in fori praticati nel materiale lapideo e fissati in posizione con malta cementizia. La stima dei carichi di progetto di strutture come i monumenti dell'Acropoli è un compito molto difficile, soprattutto quando si considera la risposta sismica. Per questa ragione sono stati impiegati con ottimi risultati metodi elaborati e precisi e strumenti analitici. Recentemente l'analisi basata sugli elementi discreti sembra predire abbastanza accuratamente la risposta di queste strutture e fornisce un metodo efficace di tempo rispetto all'uso dell'analisi basata su elementi finiti. Ma l'impiego di tali metodi per calcolare l'armatura richiesta da ciascuna frattura non è ancora applicabile su larga scala, così, per facilitare il lavoro sul sito, si utilizzano ancora metodi semplificati. Fino ad ora, il metodo di calcolo per le armature necessarie consisteva nell'adottare analogie dimensionali semplificate per le fratture, per l'armatura e per le condizioni di carico. L'articolo illustra un metodo sintetico e semplificato per il calcolo dell'armatura richiesta per elementi architettonici frammentati, tenendo conto degli effetti delle tre dimensioni spaziali (geometria della frattura, geometria del rinforzo metallico e geometria del carico). In questo approccio si tiene conto del problema del calcolo della tensione prevista dell'armatura in complesse forme spaziali di frattura. Le ricadute più significative del progetto sono in un prodotto finale che abbia il carattere di uno strumento accessibile e facile da usare, in grado di rispondere in tempo reale e facilitare così il lavoro degli ingegneri civili sul sito.

Introduction

In the Acropolis restoration projects the majority of the monuments dealt with consist of marble blocks of different shapes and sizes that are put together without the use of mortars but with very fine leveling of the adjacent surfaces and the overall structure behaves -under seismic loading- as a system of discrete blocks. Their construction was also provided with special connections, (connectors and dowels made from iron) for joining in certain places the independent architectural members together.

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Fig. 1. The Parthenon's West Façade before the restoration project. Significant fractures and missing parts are marked in.

Fig. 2. A close-up on the form of the fractures and the fracture planes.

The restoration practice follows the ancient architectural system as this was described before, and in the areas of intervention the main materials used are marble and titanium. The connections are redesigned so that in the case of activation – during an accidental loading case – the connector would fail before the surrounding marble suffers any damage.

Typical damages in ancient blocks are significant fractures and in some cases the failures are such that fragments are detached and missing from their original place. This necessitates large scale projects of joining together fragmented architectural members either fragmented ancient blocks or fragments of blocks with new complements. The common practice incorporates the use of threaded titanium bars into specially drilled holes and fixed into place with cement mortar so as to restore the unity of each discrete element of the ancient structure.

The accurate calculation of the forces that will be induced to the reinforcement during an earthquake is not an easy task, since the response of the structure is governed by the rocking and the sliding of the individual stone blocks. Previous investigations[1] on the dynamic behaviour of single freestanding columns and sub-assemblages of ancient temples have pointed out that the response of these discrete structures is highly nonlinear and very sensitive to even small changes in the parameters. Thus, the imposed excitation and the frequency content of the ground motion, the degree of the accuracy of the numerical model concerning the geometry of the structure and the assumptions adopted in the analysis (joint properties, friction coefficient, etc.) may affect significantly the results of even rigorous nonlinear analyses. For the dimensioning of the titanium bars, a methodology based on the capacity design philosophy is usually implemented ending up with the maximum forces that can be developed theoretically, independently of the earthquake excitation. The methodology of calculating the required reinforcement so far consisted of simplified two dimensional analogies of the fractures and the reinforcement as well as the loading conditions. The important features and requirements meant to be kept by this procedure was that the final product should maintain the character of an easy to use and accessible tool that would respond in real time to facilitate the work of the civil engineers on the site.

In this paper a concise and simplified methodology for the calculation of the required reinforcement for fragmented architectural members taking into account the effects of the three spatial dimensions (geometry of the fracture, geometry of the reinforcement and geometry of the loading) is presented. In this approach the problem of calculating the expected tension of the reinforcement in complicated spatial forms of fracture is dealt with.

The problem of joining fragments together – Case study: Parthenon's West Facade

A most opportune case study to demonstrate the necessities and the solutions provided are the Parthenon's West Facade and more specifically the on-going programme for the restoration of the two corners (fig. 1).

This is a typical example of the condition of the architectural members situated on the monument that have already suffered all the damages from the big fire that burnt the wooden roof and left the temple roofless ever since, the transformations to church and mosque, and also as military observatory and ammunition warehouse, that led to the big explosion, as well as all the seismic actions since its construction, and all the intervention of the previous restoration projects. It becomes obvious that 2500 years of constant use, remodelling and damages has caused severe problems to the integrity of the members. The fractures that are immediately spotted in fig. 1 are those of the architrave on the left, the orthostate of the pediment and the blocks of the retaining wall. Missing fragments can be seen also in fig. 1 in the area of the second capital, the second drum of the fourth column and the architrave on the right. The members present in most cases a multi-fragmented texture and very complicated fracture shapes as shown in fig. 2.

As described above the restoration aims at the unity of the fractured members in a way that it would bear sufficiently its corresponding loads. The technical details of joining together ancient fragments or ancient fragments with new complements are basically the same and can be seen in fig. 3.

The design criteria

The principals of the design had been set by the Acropolis Restoration Service from the very beginning of the restoration works[2]. The design criteria (fig. 4) are of two principal categories a) usual, common for every structure, such as safety and economy and b) special, due to the fact that monuments are concerned, therefore a certain aesthetic result is anticipated and respect of the ancient materials and structural techniques are factors of outmost importance.

[1] Dasiou 2007, Dasiou 2008, Dasiou 2009, Dasiou 2011, Dasiou 2012, Papantonopoulos 2003, Psycharis 2002, Psycharis 2003, Stefanou 2011.

[2] Bouras 1983.

Fig. 3. Joining together fragments with the use of cement mortars and titanium bars.

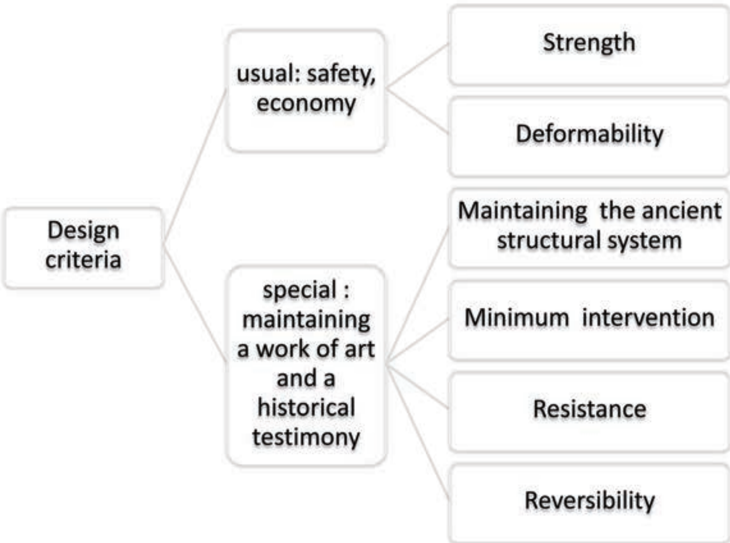


Fig. 4. The design criteria as are drown by the Service for the Restoration of the Acropolis Monuments [11].

Having to deal with monuments requires to account for not only strength and deformability, but also to meet requirements such as maintaining the authentic ancient structural system, choosing the minimum adequate intervention, using methods and material with resistance in time, and reversible if possible.

The design criteria are ruled by contradictory values such as strength and minimum intervention, resistance in time and material in use and reversibility. An optimization methodology leads to the final design and determining each time which parameter is considered more crucial.

The design methods

The design methods (fig. 5) follow the commonly used practices of all engineer works and are categorized into two main categories, after defining the design actions: the elastic method is used for permanent actions and limit states are considered for accidental actions. Usually critical are the limit states for calculating the required reinforcement. For the limit states certain types of failure are acceptable such as: opening of joints without the connector's failure, small displacements, reopening of old fractures that have been reinforced. On the other hand there are certain types of failure that are not acceptable as limit states; those include partial collapse, large displacements, marble failure at the connections and new fractures for rehabilitated members.

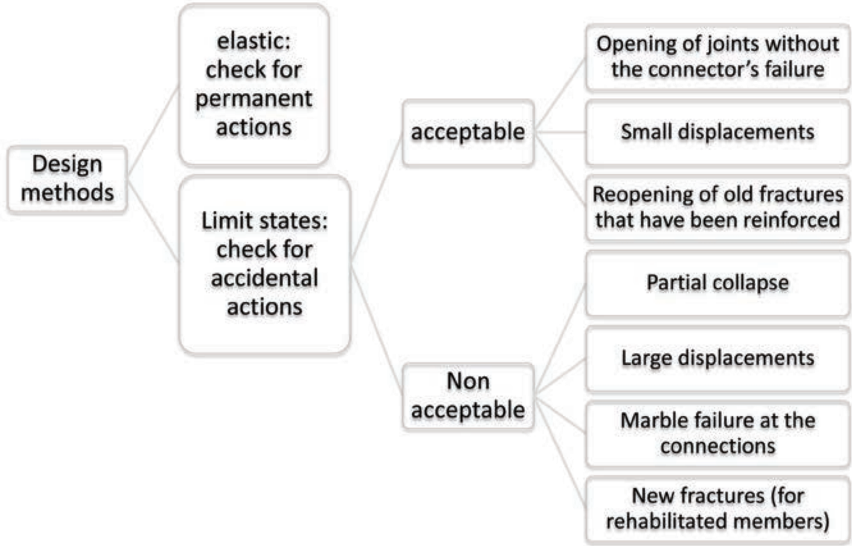


Fig. 5. The design methods as are drown by the Service for the Restoration of the Acropolis Monuments [11].

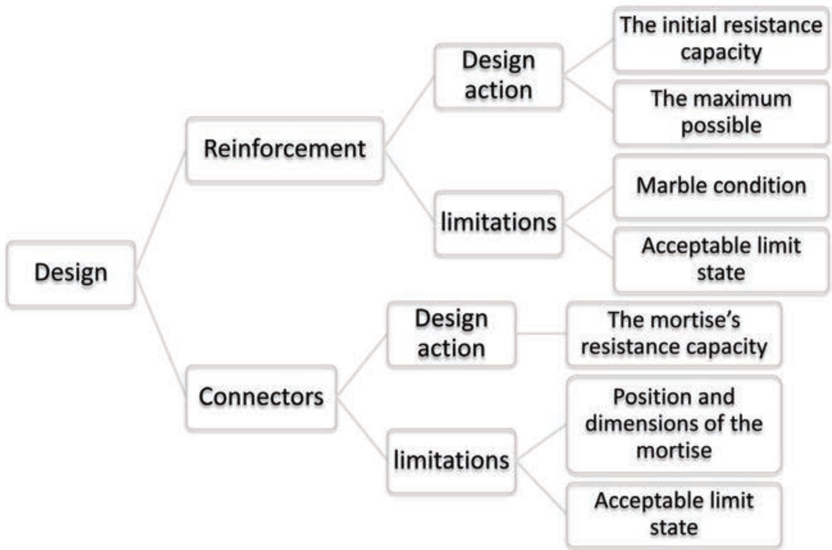


Fig. 6. The design principles as are drown by the Service for the Restoration of the Acropolis Monuments [11].

The design (fig. 6) of the overall intervention has two basic tasks to redesign the ancient connections and to design reinforcement for the fractured members. Those two tasks are similar as far the method they are dealt with, because two types of criteria are adopted for the design the first one is the anticipate design action and the second one are the superimposed limitations. For the case of redesigning the connectors for example the anticipated design action would be the mortise's resistance capacity, since a greater design action would lead to a non acceptable failure mode, the failure of the marble in the area surrounding the connection. The limitations are provided by the dimensions and position of the mortise as well as the limit state failure mode. For the case of the reinforcement design the anticipated design action could be either the initial strength of the integrated member, or the maximum probable. The initial strength of the member cannot be met with the use of reinforcement, thus the common practice would be to define the maximum probable loading that the member has to induce and use this as the design action. The limitations derive from the condition of the ancient member, and the limit state failure mode.

DEM and FEM analysis

For estimating the behaviour of the overall structure as well as parts of it and for reasons of attributing the damages and measured displacements to known actions, finite element analysis was used when the elastic theory would suffice. Those are the cases of studying the strength of the mortises in the area near the connectors[3] and studying the

[3] Zambas 1994 (a).

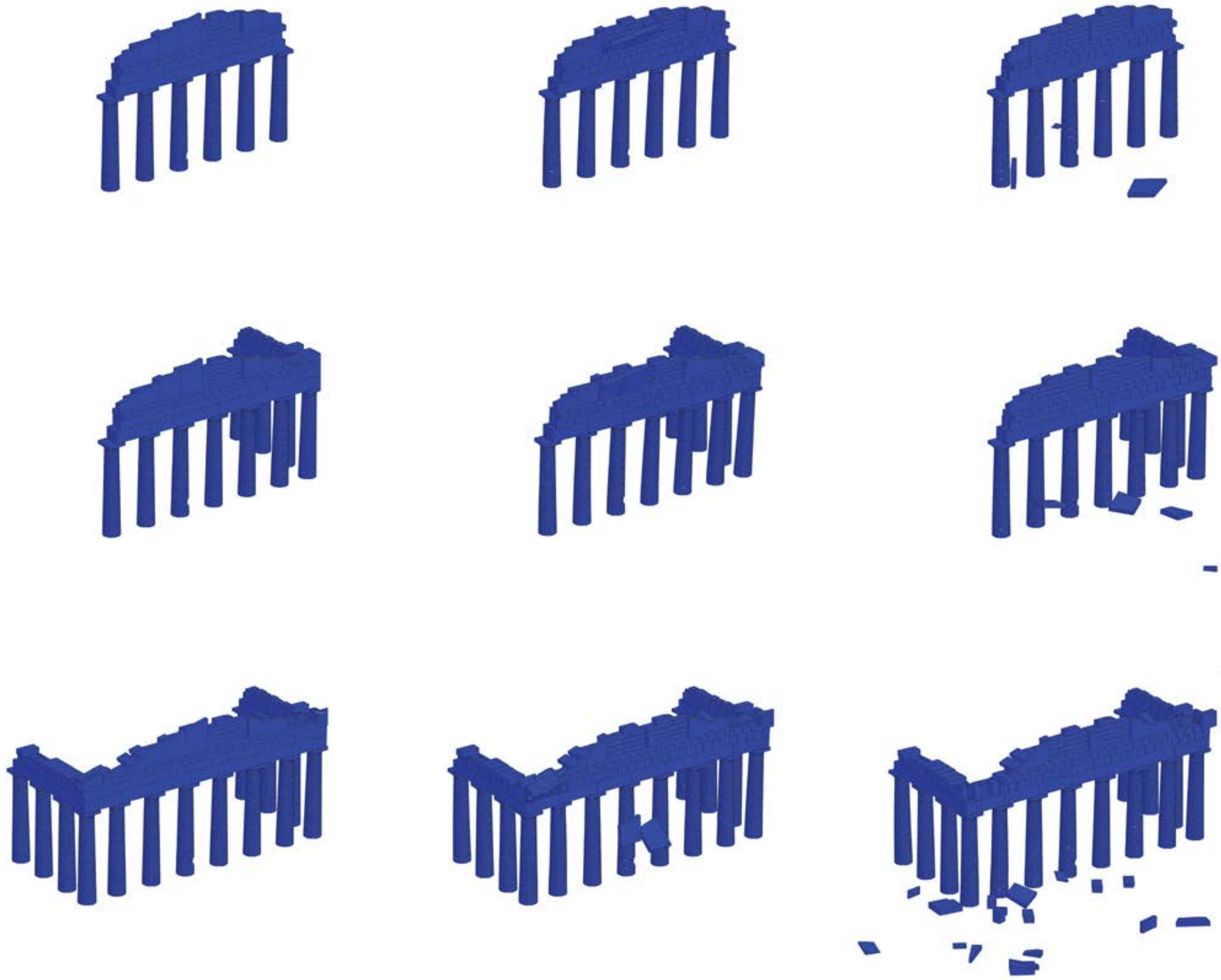


Fig. 7. The dismantlement schemes seismic study for the West Facade project using the discrete element method (Itasca's 3DEC code).

effect of the fire on the temple[4]. For the cases that the elastic theory is not sufficient to describe the phenomena of the actions- such as for a strong ground motion- non linear models of the materials and their interacting surfaces should be considered. The complexity of the structure was such that the FEM analysis though it could provide accurate prediction of the behaviour (as this was proven by experimental projects)[5], was not time effective. The latest tendency is to use discrete element analysis for structures that have this articulate structural form.

For specific reasons various elaborate studies have been carried out to predict or estimate the behaviour of part of the construction under seismic loading with analytical tools. For example this was the case of studying the scenarios of the dismantlement schemes of the West facade (fig. 7). The method used is the discrete element analysis and the code that has been implemented for that purpose is the 3DEC by ITASCA.

The use of such a method for each fragment to be joined is not for the time being feasible. The limitations have to do with the large information that would have to be inserted to simulate the actual fracture condition of each member and the time that would be required for all the data to be processed. Furthermore the studies already carried out show that the code is very sensitive to the time history inputs, thus there should be a very strict determination of the loading scenarios according to the expected actions - excitations. This kind of data is not available at the moment, because a strong motion database for near field events is not available with simultaneous registries from our net of accelerographs, so as to determine the actual enhancement or damping due to the geotechnical conditions of the site.

Further experimental results are needed to prove the correlation between analytical model and structure in order to ensure that the result of the analyses can be applied directly or with some corrections for designing the structure. The parameters have to be well determined for that purposed (material and surface coefficients).

This kind of analysis provides usually more moderate actions to be considered as opposed to the simplified methods that provide greater safety factors and thus more extensive interventions.

[4] Zambas 1994 (b).

[5] Dasiou 2007, Dasiou 2008.

Fig. 8. Three dimensional drawing of the Parthenon: present condition.

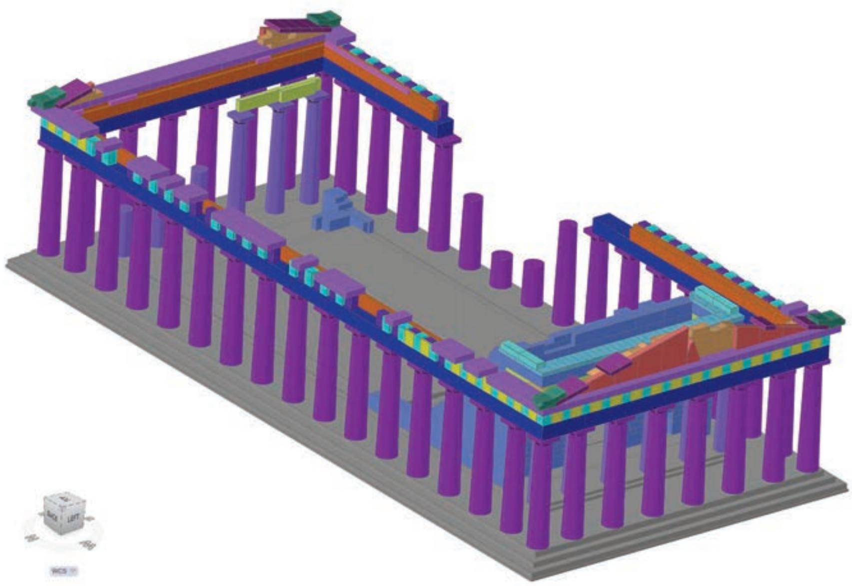
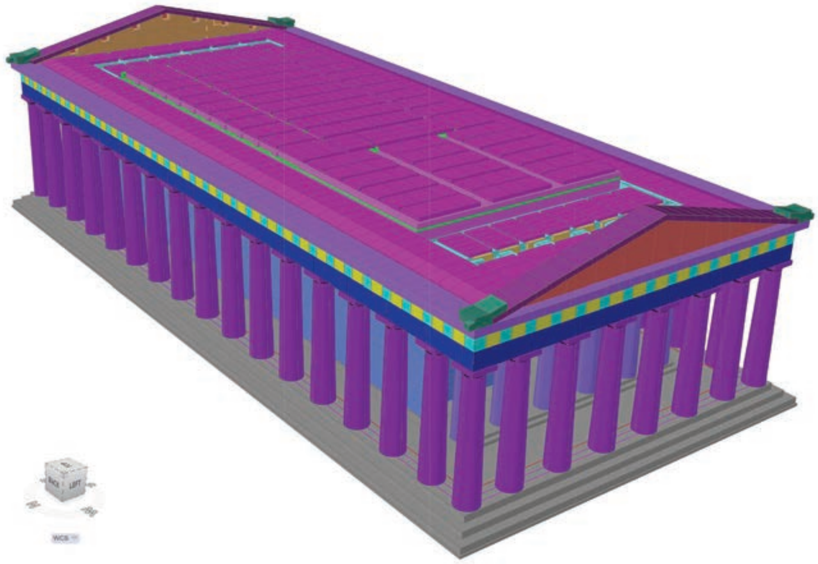


Fig. 9. Three dimensional drawing of the Parthenon: full scale restoration scheme.



Simplified simulations – Case Study: the north-west capital of the west façade of the Parthenon

The procedure for calculating the reinforcement using simplified analysis simulations sets off with a general three dimensional drawing of the structure in the final scheme of the restored condition[6].This provides information on the position of the member inside the structural system and the anticipated loads. For the case study we are working with a simplified geometrical three dimensional drawing of the Parthenon and we focus on the West Facade of the monument in its present condition (fig. 8) and a scheme of a full scale restoration of the ceilings (fig. 9).

The case study member is the north-west capital of the monument, which exhibits a complement on the upper south-west corner and a fracture on the upper south-east corner (fig. 10). The fractures have been depicted in a 3-d cad drawing where the surfaces have been described as accurately as possible (fig. 11).

It has been proven that the response of the structure is governed by rocking (fig. 12) and sliding (fig. 13) of the individual stone blocks. The principle in designing the bars is that in case of a seismic event those should bear the induced forces and maintain the discrete block as a whole, while the marble does not suffer any damage. Simplified analyses are usually applied for the design of the reinforcement that is implemented during interventions. These analyses are based on the capacity design philosophy, thus ending up with the maximum forces that can be developed theoretically, independently of the earthquake excitation. This means that rocking is simulated as a vertical concentrated or linear distributed load applied at an edge and sliding is simulated as a concentrated or distributed load that equals the force of friction between the surfaces under consideration (fig. 14).

[6] In some cases the intermediate stages have also to be considered depending on the structure and solutions given.

Fig. 10. View of the Parthenon's N-W capital from the south.

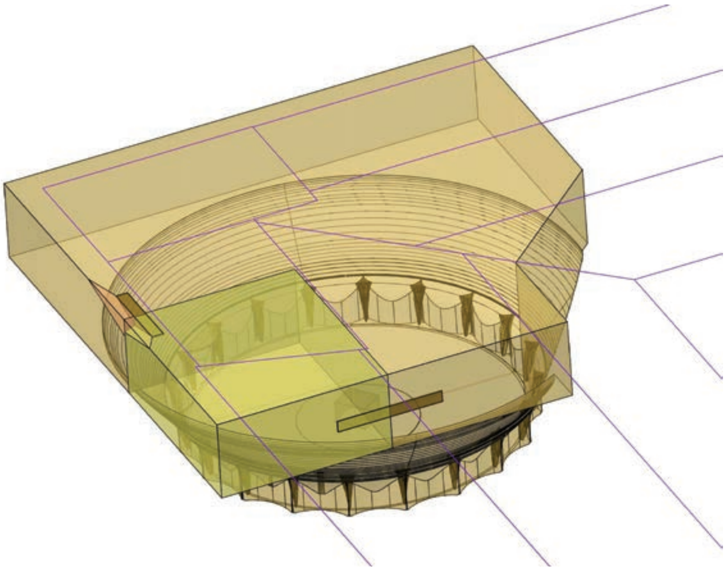


Fig. 11. Recreating geometry, the fracture planes and the dimensions of the architraves that rest upon the N-W capital in a 3-d cad drawing.

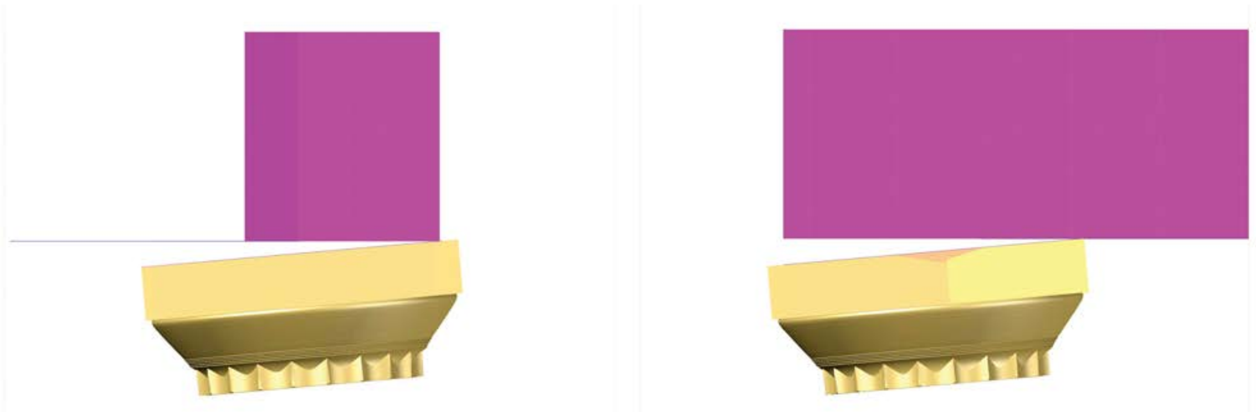


Fig. 12. Rocking at the two main axis of the monument- the movement in exaltation.

Fig. 13. Sliding at one direction plan view and view- maximum sliding towards one direction.

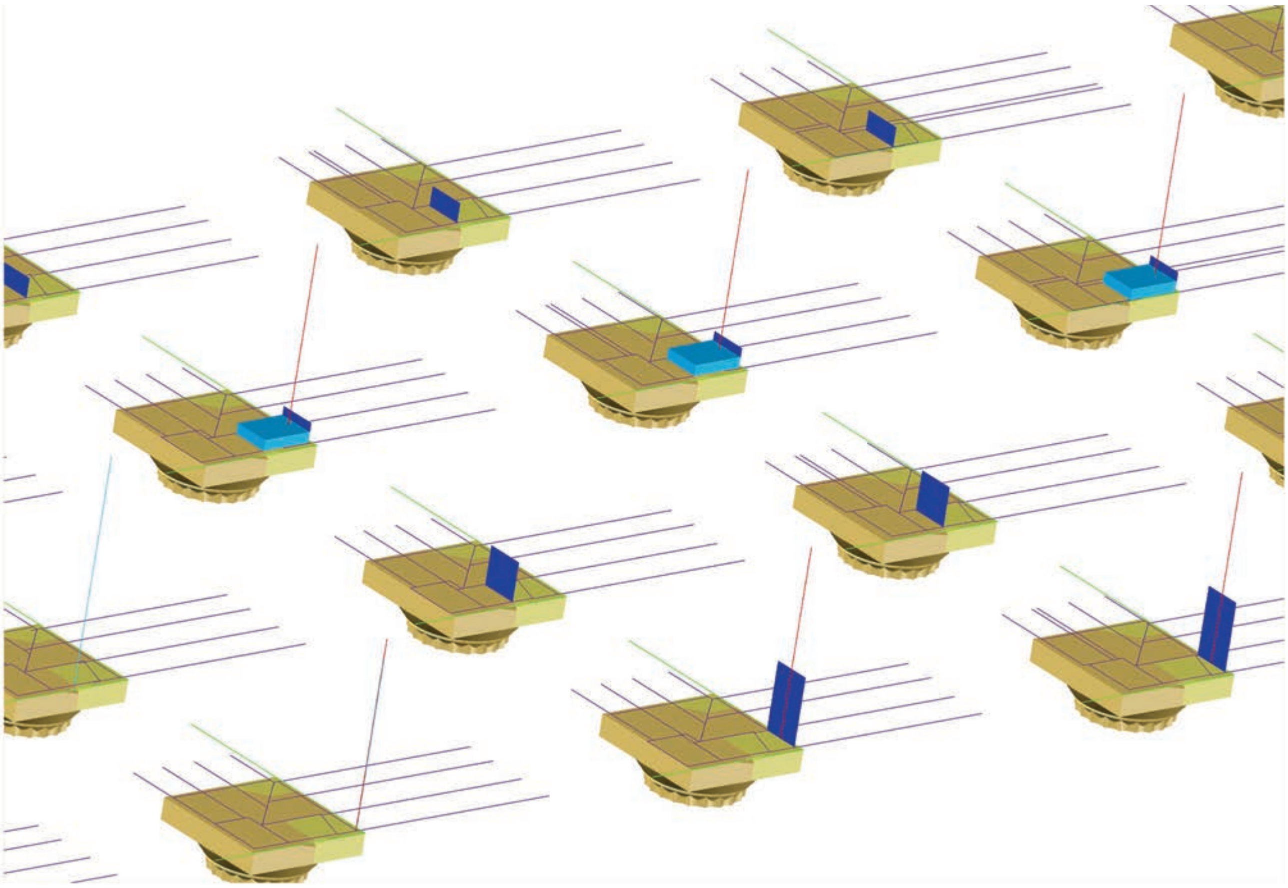


Fig. 14. Loading scenarios for the capital. Loads are considered as uniform, distributed or concentrated depending on case studied.

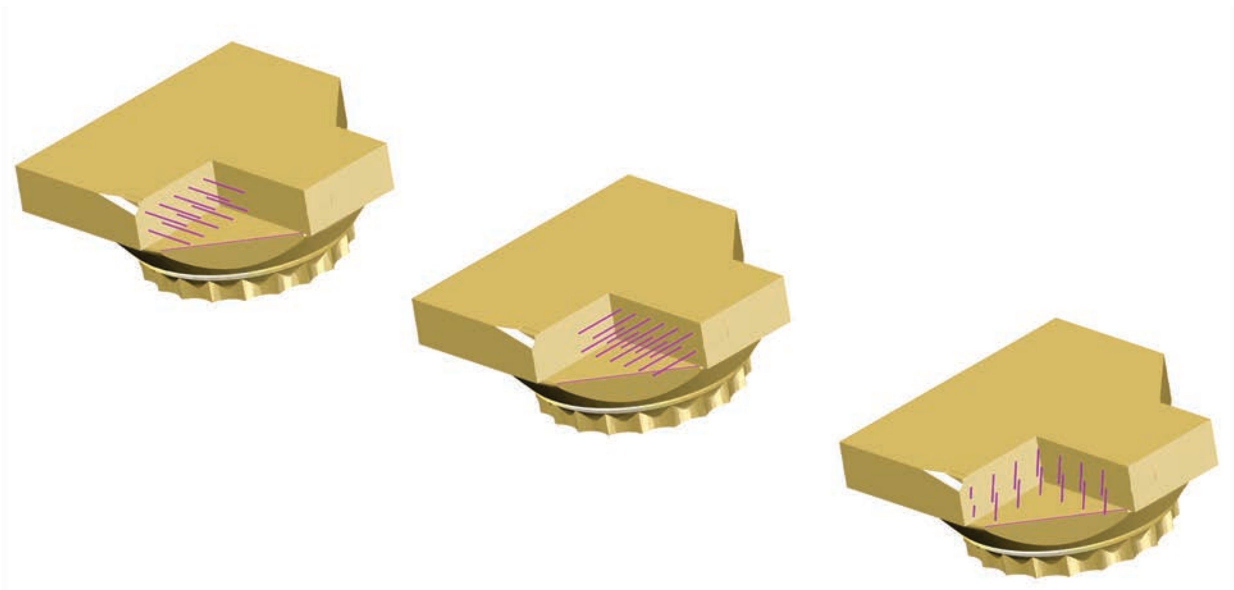


Fig. 15. Reinforcement schemes for the s-w fragment of the capital.

Furthermore optimization requires for reinforcement schemes in order to choose the most effective arrangement of bars (fig. 15). The usual case would be a three dimensional problem that a simplified two dimensional analysis cannot accurately describe.

Initial solutions were given for the two dimensional problem. The calculations are very similar to those of a typical section that consists of two materials. For joining together two pieces of marble with reinforcement bars considering a simple section (fig. 16) the principles were set at Ioannidou 2002. A simple approach for calculating the required reinforcement bars would be that those should account for the shear and axial force considering that the

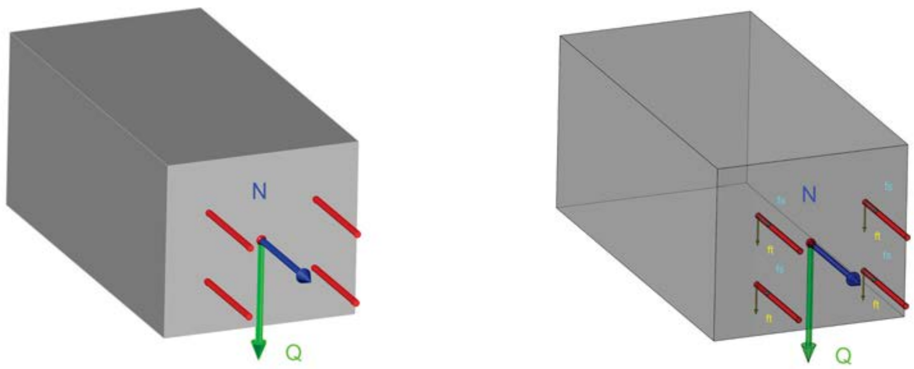


Fig. 16. Solving the problem of reinforcing a simple section in the two dimensions.

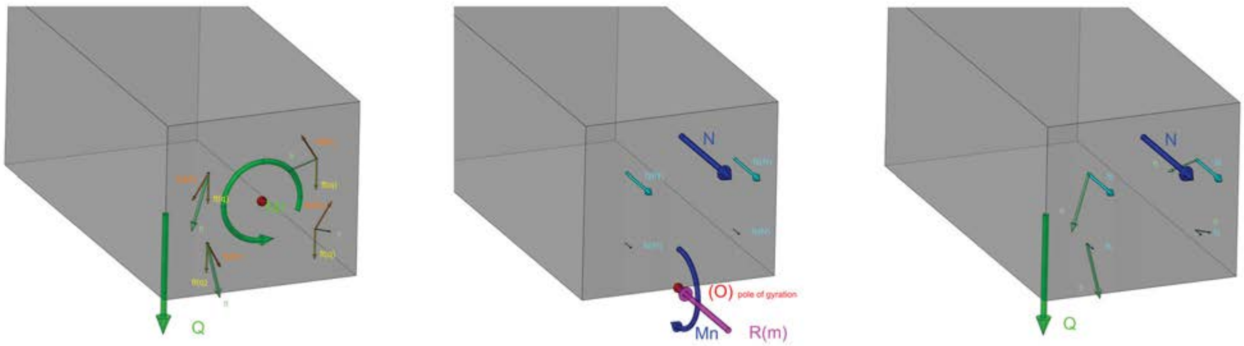


Fig. 17. Eccentric forces and calculation of tension in the reinforcement bars for the the two dimensions.

forces are acting on the centroid of the bars. The calculation ends to simple set of equations. Given the force calculated for each bar the corresponding stresses can be calculated, which cannot exceed the yield stress of the material in use (titanium) since elastic theory is considered. For the stresses the Von Misses yield criterion is adopted. The simple equations that describe the problem would be:

$$fs = \frac{N}{4}, \frac{fs}{At} < fyt \text{ (eq. 1)},$$
$$ft = \frac{Q}{4}, \frac{ft}{At_{shear}} < \frac{fyt}{\sqrt{3}} \text{ (eq. 2)}$$
$$\text{and } \sqrt{(\left(\frac{fs}{At}\right)^2 + 3 \times (\frac{ft}{At_{shear}})^2} < fyt \text{ (eq. 3)}$$

In the case that forces are not applied at the centroid of the bars, additional torsional and/ or bending moments should be calculated for the section due to the forces' eccentricity (fig. 17). The moments correspond to stresses at the bars. The torsional moment is considered as an additional vectorial shear force. The bending moment sets the section in a tension-compression state and due to the diversity of the materials (marble-titanium) we consider that the bars are being subjected to tension and at the far end of the section the marble is subjected to compression, the neutral axis -as a result of the compressive strength of the marble- tends to reach the edge of the section thus forming an axis or pole of gyration. Forming the balance equations of such a system results in general to a unique tension for each bar and every bar should comply with the requirements of the material. The equations are more complex due to the vectorial adds yet the system is still manageable and can be solved with simple calculations.

When the full three dimensional problem is considered, though, the perplexity of the equations to be solved increases, yet the main problem is always a geometrical one. Further more in the general case, the fracture planes are not following the loading axis and the reinforcement bars are not vertical to the fracture plane, neither of the same diameter, thus a programming routine was created to facilitate the calculations. Simplicity was one of the requirements that had to be met, so the routine was programmed in a simple Microsoft Office Excel sheet (fig. 18). In a nutshell, in the application created the data of the geometry of the fragment, and the loads, as well as position of potential poles of gyration, and of the reinforcement bars are imported and processed to calculate the stresses for each individual bar, which is laid out tabled. The tables are a very efficient tool to compare multiple reinforcement schemes and check multiple loading scenarios.

Check
DATA
Geometry of fragment

weight	0 kN	x		**Material of Reinfrorcement**			
	0	y		fy	300 MPa	(tension)	
0	0	z		fs	200 MPa	(shear)	
				fvm	330 MPa	(Von Misses)	
				Anchorage			
cnetroid from reference axis					25 **Øo**	(drill diameter)	
x	0 m	* measurement from the beginning of the **anchorage length**					
y	0 m						
z	0 m						

LOADS

load 1		**load 4**		**load 7**		**Fixations**
	17.2962279 kN		0 kN		0 kN	**Momemts on the membres axis:**
	22.4469875		0		0	Mx
30	9.84749972	0	0	0	0	My
distance from reference		distance from reference		distance from reference		Mz
x	-0.0204217 m	x	0 m	x	0 m	**Moments on the fracture axis:**
y	-0.0804796 m	y	0 m	y	0 m	Mx'
z	0.21931908 m	z	0 m	z	0 m	My'
						Mz'
						Moment of gyration:
load 2		**load 5**		**load 8**		MR
	24.5532875 kN		0 kN		0 kN	**Compression of the marble:**
	-2.6267269		0		0	Px
44.59820624	-37.138072	0	0	0	0	Py
distance from reference		distance from reference		distance from reference		Pz +
x	-1.4589575 m	x	0 m	x	0 m	
y	0.02744218 m	y	0 m	y	0 m	
z	2.49997132 m	z	0 m	z	0 m	

			1	2	3	4	5	6	7	8	9	10
possible poles - geometry limits	friction coeff	x	1.51737338	0	0.3	0	0.3					
	n	y	-0.07243455	0	0	0.4	0					
	0.7	z	-2.50001516	0	0	0	0.156					
		Px										
		Py										
		Pz	+									

REINFORCEMENT CENTROID		MOMENT IN THE REINFORCEMENT CENTROID		POLE DEFINITION
reinforcement centroid		Moment in the reinforcement centroid		POLE
x	-0.0204217 **m**	m	1.9826423 mx	1
y	-0.0804796 **m**		2.5730667 my	
z	0.21931908 **m**	3.438857895	1.1288051 mz	
cad	@-0.0204217448690235,-0.080479635	cad	@0.0198264233404968,0.0257306667316685,0.0112880507212982	

	N1	T1	T'1	N2	T2	T'2	N3	T3	T'3	N4	T4	T'4
x	0	-1	0	1	0	0	25.7248	-0.34	7.9039	25.7248	-0.34	7.9039
y	1	0	0	0	1	0	-15.4349	1.9998	10.2577	-15.4349	1.9998	10.2577
z	0	0	1	0	0	1	-10	-3.9613	4.5	-10	-3.9613	4.5
	θ1	θ2	θ3	θ1	θ2	θ3	θ1	θ2	θ3	θ1	θ2	θ3
cntrl		ok			ok			ok			ok	
reinforcement angle	0	0	270	0	0	0	69.7567918	-18.43493476	30.96378929	69.75679177	-18.4349	30.9638

N: is the tesion of the bar in the fragment

REINFORCEMENT DATA

bar no	bar diameter (mm)	drill diameter (mm)	bar section (cm2)	applied anchorage length (cm)	renforcement angle θ1	renforcement angle θ2	renforcement angle θ3	distance x from ref	distance y from ref	distance z from ref	shear	torsional	tensional	moment of gyration			overthrow moment		
1	8	12	0.50265482	20	0	0	270	-0.459026597	0.134349631	0.49999333	+	+	+	ok	ok	ok	ok	ok	ok
2	8	12	0.50265482	20	0	0	270	-0.459026	0.573044065	-0.499994392	+	+	+	ok	ok	ok	ok	ok	ok
3	10	12	0.78539816	20	0	0	270	0.540992084	-0.636225535	0.500048172	+	+	+	ok	ok	ok	ok	ok	ok
-4																			

DEFINITION OF THE FRACTURE PLANE
definition of fracture angles

69.75679177	α	angle of X-Y PLANE (rotation around z axis)		25.7248		-0.34		7.9039
-18.4349348	β	angle of Z-X PLANE (rotation around Y axis)	X+	-15.4349	Y+	1.9998	Z+	10.2577
30.96378929	γ	angle of Y-Z PLANE (roation around X axis)		-10		-3.9613		4.5
			a=	69.75679177	b=	-18.4349	c=	30.9638

* control check should provide ok, in other cases check accuracy
control check of right hand system
ok

TENSION LOADS on the fracture plane

shear force		**moment of gyration**	on the pole	**overthrow moment**	on the pole
H	magnitude	MR		M	
	41.8495155 Fx		1.982642334 mx		0 Mx
	19.8202606 Fy		2.573066673 my		0 My
53.7494186	-27.290572 Fz	3.43885789	1.128805072 mz	0	0 MZ
cad	@0.418495154807115,0.	cad	@0.0198264233404968,0.0	cad	@0,0,0

marble forces - sability controls

friction demand #DIV/0!

reaction demand on the pole		**reaction ability on the pole**		**forces equilibrium on the pole**		**moment equilibrium on the pole**	
F	magnitude	R	magnitude	dR	magnitude	M	magnitude
	-1.262E-11 Rx		error Rnx		#VALUE! Rnx		-1.60782E-11 Mx
	1.1372E-11 Ry		error Rny		#VALUE! Rny		1.26175E-10 My
1.7396E-11	-3.748E-12 Rz		error Rnz		#VALUE! Rnz		-2.3979E-11 Mz
cad	#VALUE!						

vertical force on the pole		**shear force on the pole**	
PR	magnitude	PnR	magnitude
	0 PRx'		-1.4631E-11 PnRx'
	0 PRy'		9.41025E-12 PnRy'
0	0 PRz'	1.7396E-11	3.25584E-15 PnRz'

final stresses on the reinforcement

bar no	bar diameter (mm)	drill diameter (mm)	bar section (cm2)	applied anchorage length (cm)	renforcement angle θ1	renforcement angle θ2	renforcement angle θ3	distance x from ref	distance y from ref	distance z from ref	σ	minimun anchorage length cm	tqmax	vm	cad
1	8	12	0.50265482	20	0	0	270	-0.459026597	0.134349631	0.49999333	102.488	10.2488	366.798	643.525	@-0.119351718132466,-0.0515158407173301,0.07(
2	8	12	0.50265482	20	0	0	270	-0.459026	0.573044065	-0.499994392	117.941	11.7941	334.932	591.987	@-0.107330652536702,-0.0592835588026142,0.06:
3	10	12	0.78539816	20	0	0	270	0.540992084	-0.636225535	0.500048172	111.285	11.1285	397.478	697.389	@-0.191812784138074,-0.087403206357589,0.135:
4					0	0	0								

Fig. 18. Concentrated form of the Microsoft Excel calculation sheet. The last table provides the information for the tension on the reinforcement bars.

Conclusions

The practice of joining together fragmented marble architectural members demanded the development of an accurate yet efficient and time effective tool for the design of the reinforcement to facilitate the work on the site. This was realized by expanding the simplified two dimensional theories to the geometry of the three-dimensional space.

A routine programmed in a simple Microsoft Excel sheet provides the tool for calculating the tension on the reinforcement bars for various loading and reinforcement scenarios. The method has been proven efficient for comparison reasons and a key to decision making procedures concerning the reinforcement schemes.

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