THE STRUCTURAL BEHAVIOUR OF COLOSSEUM OVER THE CENTURIES

M.CERONE[1], G.CROCI[1], A.VISKOVIC[2]
[1] Professor, Univ. "La Sapienza" of Rome – Dept. of Ingegneria Strutturale e Geotecnica
[2] Engineer, Univ. "G. D'Annunzio" of Chieti – Dept. of Scienza, Storia dell'Arch. e Restauro

SUMMARY

This paper concerns some of the last results obtained studying the Colosseum. To understand the Monument's present situation it was important to study, as far as possible, its structural behaviour all along its life. Many different mathematical F.E. models were carried out to simulate the various types of structural behaviours arising by the ageing, the progressive damages and collapses.

1. THE COLOSSEUM HISTORY AND ITS STRUCTURAL BEHAVIOUR

The Flavious Amphitheatre, built on the bottom of the Labicana Valley, was in a first time inaugurated in the year 80a.C. during Emperor Tito's kingdom, after about ten years of works including many foundation works; some works were completed few years later in the Arena and probably in the attic level.
The foundations stand on a heterogeneous ground not completely known (and now under study) formed by recent Holocene alluvial deposits less compact and less resisting then the underneath Pliocene stratification. The reduced soil stiffness, not homogeneously distributed under the monument, is the cause of some first differential settlements, relative movements and the consequent increasing of local stresses. Thus during the first earthquakes it was facilitated the concentration of the major damages on the southern part of the monument. The other earthquakes happened along the centuries (together with the degradation due to the weathering and some removing of unsafe portions) bring up to the present not symmetrical aspect of the survived structures.

According to historic sources great damages took place with the fire in the year 217; important restoration works were carried out from 218 to 223 and were completed only in 238 (stopping the games in the Severian time), but probably these damages were amplified by the earthquakes in the year 217 (Dione Cassio, but uncertain) and 223 (9 September or 19 October): the *Chronicon Paschale* defines these seismic events as very strong (we can evaluate them in the range of the 5th grade of the Mercalli Scale), while in the *Historia Augusta, Al. Sev. 44.8*, it is mentioned that Alessandro Severo was particularly economically engaged in repairs after such earthquakes. It is certain that great damages to the monument (in the Cavea, on the Podium and on portions of the attic wall, but particularly to the attic columns that fell down in the Arena) were caused by the 5th century earthquakes and particularly by that of the year 442 (or 443), considered in the range of the 8th – 9th grade of the M.S., and by that of the year 484 (or 508) not so strong but probably more destructive according to the documented reconstruction works that followed. The repairs were not always completely oriented to rebuild: the Arena hypogeum structures were completely filled and covered by earth while some southern arcades were dismounted as it was considered the best solution for safety reason. It must be taken into account that in the beginning of the 6th century, the progressive reduction in the Roman population brought to a reduced demand of sitting places in the Amphitheatre. To these restoration works are referred some epigraphs (discovered in the 18th century) where Teodosio II, Valentiniano III and Decio Mario Venanzio Basilio are mentioned.
The last games were held in 519 and in 523 after a long period of absence, with the authorisation of Theodoricus (although he did not like them).
For a very long period the Colosseum fell into neglect until reused in the late middle age by human settlements. The structure remains standing but locally damaged where vegetation grows in the wall cracks increasing the damage itself. Smaller earthquakes weakened the structure until 801 when a strong earthquake (9th grade M.S. with epicentre in the Apennine region) caused collapses in the St. Paul's Basilica and certainly increased damages in the Colosseum external arcades on the south-east side. In the late middle age it is documented the presence (13th century) of the Frangipane palace (later Annibaldi) replacing the porch near the eastern entrance. In the same time the important link with the Labicana Valley was possible only along the monument northern side or through the monument itself, as probably along the southern side there was risk of collapses. However the standard of conservation was still satisfactory, in spite of the damages, in order to allow the use of the area.
A new destructive earthquake with epicentre on the central Apennine mountains (8th – 9th grade M.S.) took place in 1349 as testified by Petrarca. This earthquake, which also damaged the Tempio della Pace, St. Paul's and St John's Basilicas, the Conti Tower and the Milizie Tower in Rome, caused in the Colosseum the collapse of a large portion of the southern porches.
After the 1349 earthquake the Colosseum was neglected. Thus the ruins accumulated inside and on the Celio side (the southern side) were used to pick up building materials. The maintenance of the northern front is due to the better static conditions and to the interests to maintain a monumental front on the important public route between the Laterano palaces and downtown. In 1703, at the time of the last strong earthquake (which caused the destruction of L'Aquila city in the central Apennine mountains), the structural condition of the Colosseum was not very different from today, at least from a geometric point of view, even without the reconstruction of the 19th century. Considered that this earthquake was as strong as that in 1349 still the damages were not so widespread (the collapse of two arches in the second ring is documented). In any case the existing damages were increased.

In the 18th century, in spite of some local reconstruction and of the decision to stop the plunder (Benedetto XIV) the structural stability is getting worse. Moreover some even weaker earthquakes in the second half and in the end of the 18th century brought to the critical situation which claimed the great restoration of the following century.
In the 19th century two buttresses were built to support what remains of the outside façade; the first at the east side (R. Stern 1805-1807), the second at the west side (G. Valadier 1820-1826).
Moreover, missing structure in the south side near the minor axis were rebuilt (G. Salvi and L. Canina 1846 – 1852). On the northern side radial walls and vaults at the first order (seven arches) and at the second order (eight arches) were rebuilt. Particularly were rebuilt some internal walls and vaults attached to the external wall at the third and attic level, near the minor axis, in order to allow radial chaining. These works partially recovered the annular and radial stability. In the 20th century there is the intervention in 1979 (Valnerina earthquake), carried out by the Soprintendenza Archeologica di Roma according to a project of G. Croci, to reinforce the five pillars of the XVI, XVII, XVIII and XVIIII arches of the third ring (now the outside ring on the south-east side) that were badly damaged and could collapse. The arising of that danger situation was the occasion to start studies, researches, the investigations and the always more careful and deeper present analyses.

2. THE MATHEMATICAL MODELS OF THE STRUCTURAL BEHAVIOUR

In order to study the structural behaviour three are the main phases in the two thousand years of the long historical life of the monument. To these phases are referred the geometry of the mathematical models used in this study. Other models may then derive from each one of these main models taking into account possible variations of some parameters not yet well known (as for instance the soil and the foundation stiffness) or the influence of the connection, between different masonry structures, which efficiency may have changed along the time due to damages and to interventions.
The structural analyses use, in this study phase, global elastic F.E. models which geometry and mechanical characteristics are the following:

- models of the original situation of the Flavian time that consider the interaction with the soil low stiffness and the effect of the first earthquakes (fig. 1),
- models relative to the situation before the 19th century interventions (fig. 2),
- models according to the present situation (fig. 3).

In the analyses of the first group of models, the stratigraphical situation of the soil, still not completely known for lack of specific investigations and relative geotechnical tests, has been modelled according to the hypothesis of the most recent studies on that valley (based on general evaluations at regional scale and on some stratigraphical data relative to nearby areas). Under the southern base area of the Colosseum there are less stiff soil strata in a curvilinear trend as the Labicano ancient stream that has originated those strata themselves. Conversely on the northern side the foundations rest on more resistant and stiff sediments (fig. 4). To these two different foundational soils correspond, in the models, different stiffness for which are tried different reciprocal ratio (i.e. 1:1, 1:5 up to 1:16) in such a way to take into account the present uncertainty of knowledge. As regard the definition of the seismic actions, considered in all the models, it has been taken into account the historical data relative to the registered events (7th – 9th grade M.S. with a return period of about 300 – 500 years) as well as the studies of the seismic characteristics of the roman seismological region. Such studies agree in the definition the return period of 400 – 500 years, the maximum "magnitude" equal to about 7th grade M.S. and the highest acceleration equal to 0.05 – 0.06g. The results of the analyses relative to the original configuration (the Flavian time structure) clearly show that the damages, with the distribution and succession of collapses historically documented, are due both to the non homogeneous stiffness of the soil (fig. 5 and 6) and to seismic actions producing adverse combined effects in the area of the east entrance and in the southern sector (fig. 7 and 8).

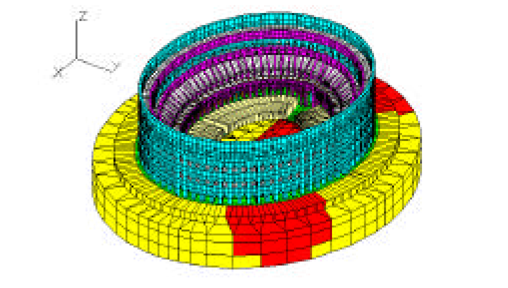


Figure 1 : The Flavious Amphitheatre model with the foundational soil

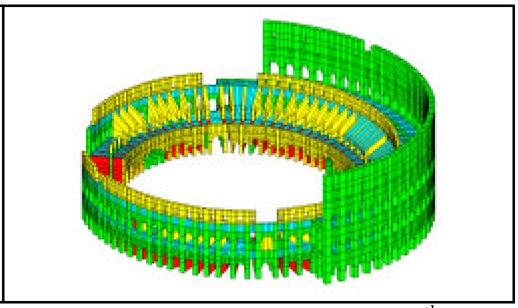


Figure 2 : The structures before the 19th century restorations

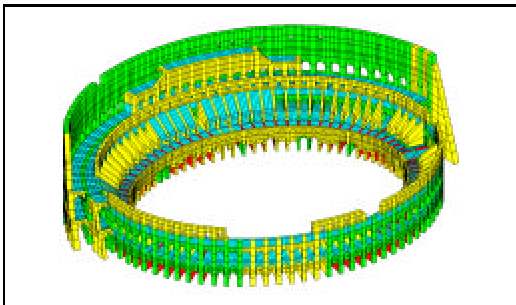


Figure 3 : The present situation

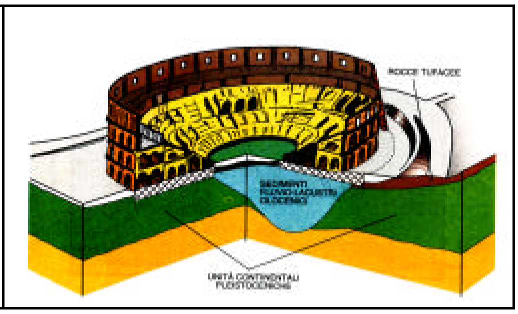


Figure 4 : Schematic geomorphological situation of the site

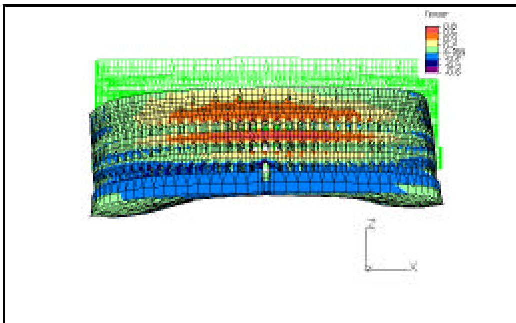


Figure 5 : Annular tensile stresses and deformation, north side view

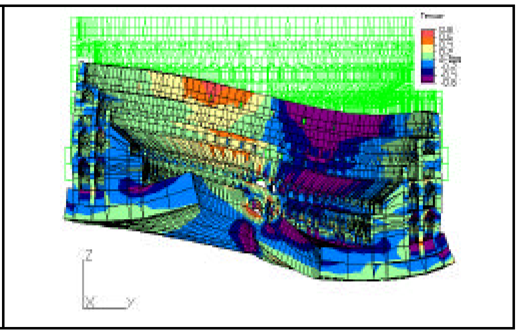


Figure 6 : Section with annular tensile stress and deformation, east side view

The settlements and the soil movements would not have been able to produce, alone, the registered collapses, but certainly they contributed to make more critical the effects of the firsts earthquake. The following, along the centuries, successive earthquakes (fig. 9), together with the progressive lack of maintenance and the subsequent violations, have caused the development of asymmetrical damages and collapses, mainly spread on the Celio side according to the historical documentation and the present situation (fig. 10, 11 and 12).

3 ACKNOWLEDGEMENTS

This study is carried out in compliance with the Agreement among the University of Rome “La Sapienza”, the Ministero dei Beni Culturali ed Ambientali, the Soprintendenza Archeologica di Roma and the Bank of Rome.

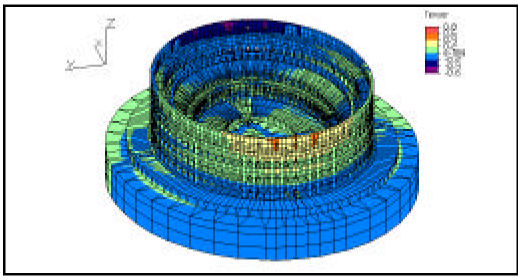


Figure 7 : ?$_y$ stresses with the seismic action directed according to the major axis direction

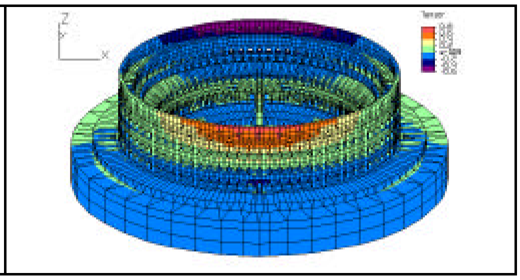


Figure 8 : ?$_x$ stresses with the seismic action directed according to the minor axis direction

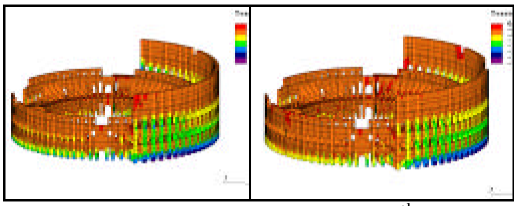


Figure 9 : Vertical stresses in the 18th century situation and seismic actions alternatively directed along the two main axes

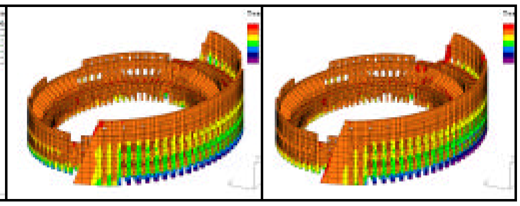


Figure 10 : Vertical stresses in the present structural situation and seismic actions alternatively directed along the two main axes

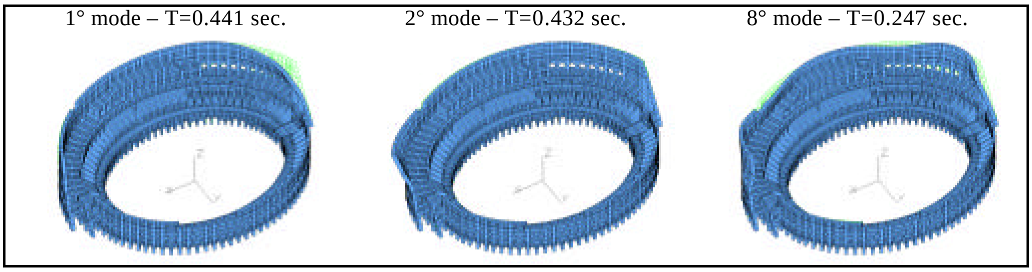
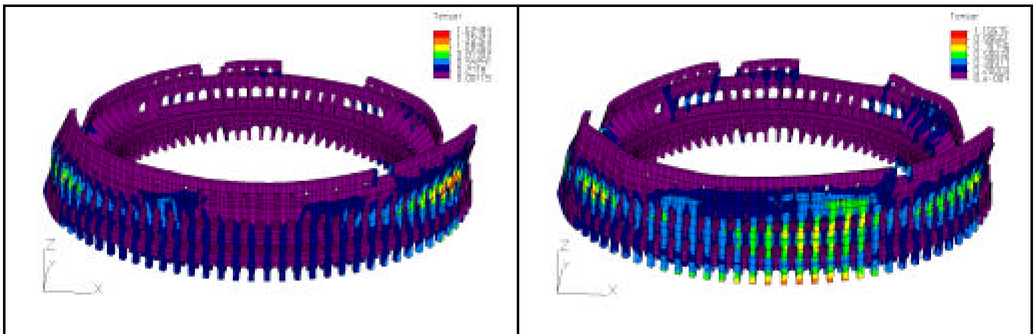


Figure 11 : Modal analysis with the model of the present situation



Modal combination with the seismic action directed according to the main axis

Modal combination with the seismic action directed according to the minor axis

Figure 12 : Dynamic analysis with the model of the present structural situation; displacements and vertical stresses

4 REFERENCES

[1] AA.VV. – "Il Colosseo", in *Archeo – Dossier*, 21, nov. 1986.

[2] AA.VV. - *Il Colosseo*, Electa, Roma 1999.

[3] Baratta M. – *I terremoti d'Italia*, rist. anast., Torino, 1901.

[4] Cerone M. et al. – "Analisi e documentazione dei dissesti strutturali del Colosseo ed individuazione delle situazioni di rischio" , in *Studi sul Restauro del Colosseo* , Quaderno 1, Roma 2000.

[5] Cozzo G.- *Ingegneria Romana*, Roma 1928.

[6] Cozzo G.- *Il Colosseo. L'Anfiteatro Flavio nella tecnica, nella storia delle strutture, nel concetto esecutivo dei lavori*, Roma 1971.

[7] Croci G. - *Studi e ricerche sul Colosseo*, Dip. Ing. Strutt. e Geot., Roma 1990.

[8] Funiciello R., et al.- "Seismic damage and geological heterogeneity in Rome's Colosseum area: are they related" - *Annali di Geofisica*, vol. 38 (5-6) Nov-Dec 1995.

[9] Guidoboni E. – *Catalogue of ancient earthquakes in the Mediterranean Area up to the 10th century* -I.N.G. , Roma, 1994.

[10] Lanciani R. – *Rovine e scavi di Roma antica*, Quasar, Roma 1985, trad. dall'originale The ruins& excavations of ancient Rome, London 1897.

[11] Lynne C. Lancaster – "Reconstructing the restorations of the Colosseum after the fire of 217", *Journal of Roman Archeology*, vol 11 Portsmouth, Rhode Island 1998.

[12] Migliari R. "Ricerche sulla forma del Colosseo", - in *Studi sul Restauro del Colosseo* , Quaderno 1, Roma 2000.

[13] Moccheggiani Carpano C., Luciani R. – "I restauri dell'Anfiteatro Flavio", in *Rivista dell'Istituto Nazionale di Archeologia e Storia dell'Arte*, serie III- IV, 1981.

[14] Moczo P., Rovelli A., Labàk P., Malagnini L. – "Seismic response of the geologic structure underlying the Roman Colosseum and a 2-D resonance of a sediment valley" in *Annali di Geofisica*, vol. XXXVIII N. 5-6, November-December 1995.

[15] Rea R.- "Il colosseo e la valle da Teodorico ai Frangipane", note di studio in *La storia economica di Roma nell'alto medioevo*, Firenze 1993.

[16] Sabetta F., Paciello A. – "Valutazioni della pericolosità sismica" in I.P. e Z.S. *Memorie descrittive della carta geologica d'Italia*, vol. L, Roma 1995.