NUMERICAL EXAMINATION OF DIFFERENT MASONRY STRENGTHENING METHODS

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SUMMARY

Numerical analyses were performed on masonry box-buildings under horizontal loads with and without steel strengthening elements. Definition of geometrical model and material properties, as well as of the loading action is described. Results obtained by the numerical calculus program have been compared to one another in order to evaluate the suitability and effectiveness of a few steel refurbishment methods applied to masonry buildings. Some possibilities for future development in this field are listed at the end.

Keywords: refurbishment, strengthening, tie-bars, gridwork, modelling, seismic action

1. INTRODUCTION

The masonry buildings represent one of the best known and the most widespread constructions. These kinds of structures have been built since very ancient times, moreover until the 18th Century or so they were almost the only solution to create a new building. Although since that time the role of masonry as the main load-bearing structure has gradually decreased and has been replaced by other materials (e.g. steel or reinforced concrete), particular attention must be paid to the mechanical performance and implementation procedures of these constructions by the building industry and the engineering research of today and, with absolute certainty, of the future, too.

Amongst the countless masonry structures from all around the world, there is a large number of monuments, churches and old historical buildings. For the reference, a mention must be made that in Italy the stone masonry churches were especially widespread and popular, corresponding to different historical eras and their trends of style. These latter masonry churches and their examination in case of required restoration works were considered to establish the structural model.

Although the masonry structures have appeared to be very durable, time after time these old structures often suffer from several types of structural failures, such as extensive cracking or partial collapse of walls, damage of masonry crossings and corners, disconnection of walls, etc. On the other hand, it is very often necessary to improve the structural behaviour of masonry buildings, in respect to certain new load cases (due to, for example, new type of functional use or recent environmental effects). As a consequence of the aforementioned facts, *refurbishment* of these old masonry constructions is strongly needed for the preservance in a lot of cases. This strengthening and upgrading

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activity is to be carried out generally due to public, architectural, economic and/or, of course, structural interests. Moreover, in such cases of required refurbishment the structural steel has been acknowledged as a suitable material in every respect (Mazzolani, F.M., 1990).

It is also very well known from the earliest times that the tensile strength of masonry materials is much less than their compressive one, therefore it is often neglected. That is why masonry structures have quite different load-carrying capacity with regard to various loading directions. In fact, masonry walls as main load-bearing structures are generally able to carry the vertical loads in a very safe and stable way, while they are, obviously, rather sensitive from structural point of view in case of horizontal loads. In this latter case the masonry wall tries to behave as a plate under bending, whereby undesirable tensile stresses may arise easily even in case of relatively low load intensities.

On the basis of the facts stated above, this paper aims to appraise the suitability and effectiveness of a few typical refurbishment methods using structural steel on masonry box-buildings, under horizontal loading action. To receive the expectation base points for assessment, a finite element analysis program named STRAUS was used, various cases were analyzed whereas a linear method of computation was applied.

2. EXAMINED CASES

The masonry box-building, considered in a very simple way to be suitable for the required analytical examination, has been arranged in a rectangular form in plan with just external walls, and neglecting any kind of floor or roof structures.

Without steel strengthening two types of this structure were chosen in order to take some idealized yet practical attributes into account (Fig. 1):

- *(a)* ideal masonry box with continuous and intact walls,
- *(b)* intact masonry uprights of the box-building with a few wall-openings (doors and windows) as in reality.

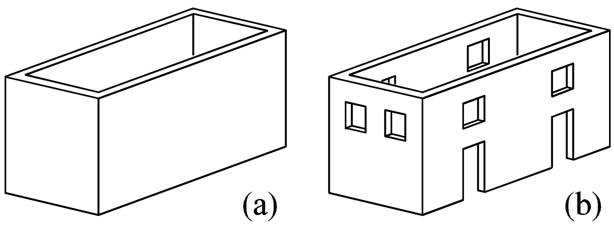

Fig. 1 Types of structures examined

Going on, with strict reference to the Italian church buildings and other historical masonry monuments as mentioned before, the *strengthening methods* consist of three kinds of frequent structural solutions, particularly (Fig. 2):

- *(1)* post-tensioned *vertical steel tie-bars* inside the masonry walls along the entire height,
- *(2)* post-tensioned *horizontal steel ties* inserted in the panels closely to the top level,
- *(3)* *gridwork on the top* of masonry building, with steel I-section members.

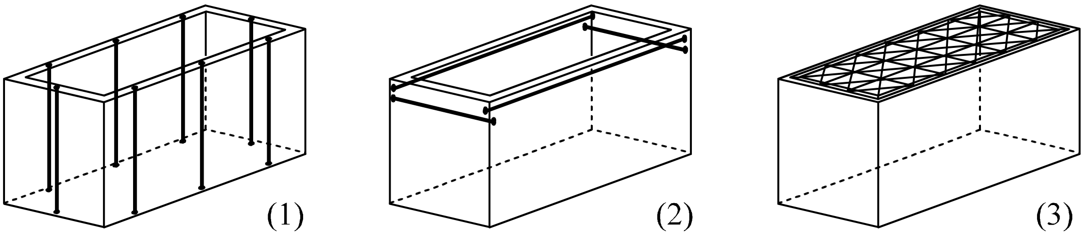

Fig. 2 Examined strengthening methods

Of course, these strengthening works (Mazzolani, F.M., 1990) can be used for both types of structures, so all the possible combinations of these cases have been also studied.

3. INITIAL DATA ADOPTED FOR THE ANALYSES

3.1 Definition of the geometrical model

As stated in previous sections, the geometrical model of the structure was established according to the approximate average dimensions of old medieval churches and historical buildings, which means a simple masonry building with rectangular shape of plan by 10*20m, with 10m of height and 1m of thickness for the four external walls. From the point of view of the evaluation, the geometrical dimensions represent just parametrical values, thus the afore-described box-model has appeared to be sufficient to use in this subject. Furthermore, allowing for the symmetry of both geometry of the model and loading action (see later), just half of the masonry box has been considered for the computer analyses, as shown in Fig. 3. The boundary conditions have been set up in such a way so that both the fully clamped base-supports and the symmetry of the structure were consistently taken into account.

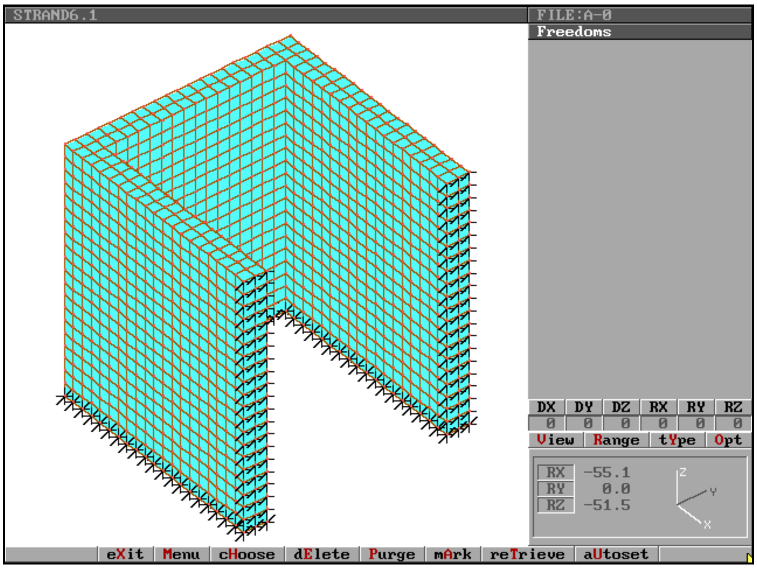

Fig. 3 Numerical model calculated with the STRAUS software – undeformed initial geometry

The component finite elements of masonry walls have been decided to be of 8-node 3D brick elements with an edge-length of half a meter on each side. This FE mesh could enable the steel reinforcing 1D finite elements to be integrated to the model in a very simple way, at the middle of the thickness of the walls in the required place and position, being joined through the existing nodes of corresponding brick elements.

Geometrical dimensions of the steel component parts were defined based on restoration works realized frequently in engineering practice. Accordingly, the diameter of the circular cross-section of the steel ties was chosen as 20mm. The lattice gridwork on the top is made of structural steel I-sections with a height of 200mm, a width of 100mm and arranged in plan by, except for the outer fields, 2.5*2.5m meshes with horizontal X-diagonals in order to ensure the high in-plane stiffness.

3.2 Mechanical properties of materials

It would be one of the most difficult tasks to say if one needed to know how high the accurate numerical values of certain mechanical characters of masonry materials are. In fact, considering masonry buildings, there are many different factors which can play a significant role in respect to its mechanical features, whereby they have a vast influence also on the load-bearing capacity of the whole structure (Livingston, R.A., Fitz, S. and Baer N.S., 1990).

However, in the calculus method, values concerning the physical properties of masonry material have been established based on statistical analysis of test data on sandstone building material found in the literature. In particular, it means that the values assumed in this research are equal to γ=18kN/m^3 as the specific weight, ν=0.15 as the Poisson coefficient and E=800N/mm^2 as the elastic modulus. In this way, the material of masonry walls has been assumed to be isotropic and homogeneous.

Properties of the steel material of refurbishment elements represent an easier and simpler task to be defined due to prefabricated application of structural steel. So, in these computer analyses, the following usual material features have been considered for steel elements: specific weight of γ=78.5kN/m^3, elastic modulus of E=206000N/mm^2 and thermal expansion coefficient of $\alpha=1.2*10^{-5}$ °C^{-1}.

3.3 Loading actions

Selfweight of all elements was adopted to the analyses by defining the direction of gravity, and thus, considering the specific weight and the geometric dimensions of the structural parts, the gravity load was taken into account automatically by the software.

As already stated in the introduction, the direction of external loading action was decided to be horizontal with regard to the case that provides the least load-bearing capacity for vertical masonry uprights. Moreover, as the most extreme horizontal loading effect, *seismic action* has been considered. But, the complicated dynamic influence of earthquakes has been assumed by static approach allowed by several National Standards in a lot of countries and by Eurocode 8, too. By adopting this static approach, inertia forces acting on the walls can be approximately evaluated considering a force distribution directed according to the first vibration mode of the structure with linear assumption. In case of box-buildings studied here, there are two kinds of load-distributions. For masonry buildings without reinforcing and for those strengthened by steel ties, the linear distribution of the loading action has a value of zero at the base and a maximum value at the very top of the structure, corresponding to the first vibration mode of a free-standing column as a one-degree-of-freedom system in the direction of horizontal load (Fig. 4). If the masonry box is refurbished by steel gridwork on the top, a bi-linear force distribution is assumed, by zero value at both the base and the top whereas by maximum value at the middle of the whole height (Fig. 4). This can be supposed because, thanks to its great in-plane stiffness, the gridwork is able to absorb the inertia forces of the “weak” walls – namely those normal to the seismic action so being under bending effect dominantly – and to transfer them to the “strong” walls which are parallel to the quake direction so mainly exposed to membrane effect. Therefore, with respect to the relatively small displacement of the “strong” walls in the direction of the action, the top of the whole structure could be assumed to remain at the original position also after deformation – for modelling the loads in this sense (Mazzolani, F.M. and Mandara, A., 1995). At the computational model, following the regarded distribution along the height, the load was applied to the structure by every single brick element as uniformly distributed pressure on the proper side. The volume of resultant force by one meter in horizontal direction is 10kN/m, representing just a numerical parameter for comparison.

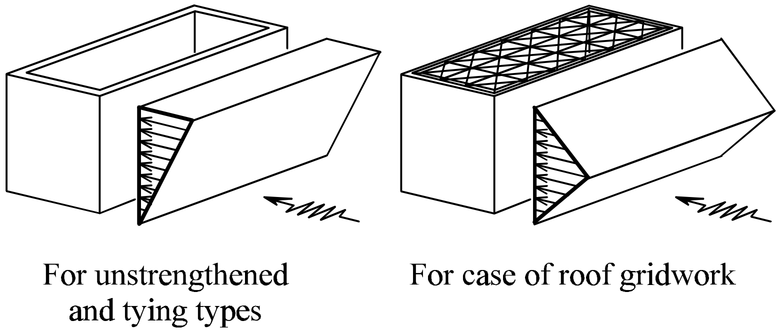

Fig. 4 Distribution of horizontal loading action

Finally, the *post-tensioning* of steel tie-bars as an internal load was modelled in such way that the stresses were input as the effect of thermal load, namely by uniformly distributed cooling. Temperature reducing of 24°C for just steel ties has been determined as not to cause higher normal stress in the masonry with this intervention than tenth of the compressive strength of masonry material (σ_c=6N/mm^2 value was assumed for the sandstone), which is a very frequent and simple method to design the post-tensioning force in practice.

4. RESULTS OF CALCULATIONS AND COMPARISONS

The calculations have been carried out, as aforesaid, by the finite element software STRAUS, using linear analysis solver function.

The most significant numerical results are reproduced in Tab. 1, concerning important output characteristics. (Notations of the cases are derived from the symbols used in Figs. 1 and 2 from chapter 2, and in addition, (0) indicates no strengthening on the masonry.) The highest tensile principal stress σ_{11} can play a very significant role with regard to load-bearing capacity of the entire masonry construction since that one, after reaching the very small value of tensile strength of masonry material, is able to cause the localized places where failures (cracks or partial collapses) first occur. The magnitude of shear stress σ_{xy} (x and y axes represent the two perpendicular horizontal directions of masonry walls) has a high influence in the development of dangerous cracks causing

Structural types	Strengthening methods	σ_{11}^{max} [N/mm^2]	σ_{33}^{max} [N/mm^2]	$\lvert\sigma_{xy}\rvert^{max}$ [N/mm^2]	$\lvert\sigma_s\rvert^{max}$ [N/mm^2]	d_y [mm]	p [%]
(a)	(0)	0.146	–0.326	0.036	–	7.37	0
	(1)	0.147	–0.327	0.036	53.10	7.36	0.020
	(2)	0.137	–0.324	0.035	65.75	7.34	0.015
	(3)	0.060	–0.319	0.023	177.3	1.35	1.683
(b)	(0)	0.175	–0.386	0.041	–	8.29	0
	(1)	0.175	–0.384	0.041	52.95	8.28	0.022
	(2)	0.167	–0.387	0.040	64.74	8.25	0.017
	(3)	0.096	–0.335	0.023	177.4	1.51	1.900

Tab. 1 Comparison between some numerical results

disconnections at the wall-crossings and corners. In the sense of these two values of general stress state it can be observed that the various examined steel strengthening methods provide also quite different effectiveness for masonry. Results show that vertical tie-bars, in this kind of application as adopted for computing, do not reduce the magnitude of the general stress state of masonry walls whereas using horizontal ties a significant decrease can be reached. By the calculus program the most effective solution has been found to be the roof steel gridwork by means of which the maximum value of principal stress σ_{11} could be reduced by 50 per cent approximately, for instance. But it is worth to mention that in this latter case the normal stress in steel elements (σ_s) reached the highest value, so the correct and economic design of the gridwork is very important and necessary.

Furthermore, it should be also very interesting to observe what the distributions of these types of stresses are like. Figs. 5 and 6 show the distribution of principal stress σ_{11} and shear stress σ_{xy} in case of unstrengthened original masonry box (type “a” – strengthening method “0” or shortly: a–0), respectively. Fig. 5 shows indeed that maximum stress values indicating strongly tensioned parts on the structure are located at the corners and in the intermediate vertical cross-section of the “weak” walls, on the upper places. On the other hand, the highest shear stresses σ_{xy} are concentrated along the masonry walls also close to the top, as it is reproduced in Fig. 6. In case of tie refurbishment types (a–1 and a–2) these stress distributions are almost the same, while on the ma-

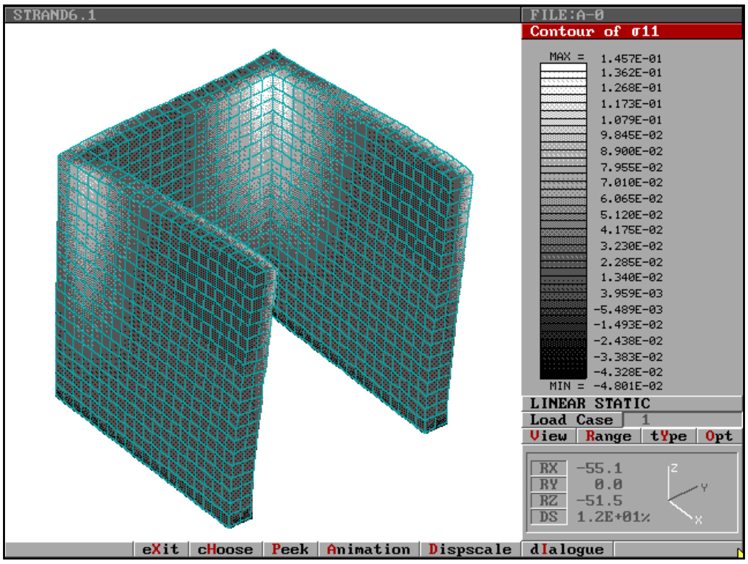

Fig. 5 Distribution of s₁₁ stresses on deformed shape

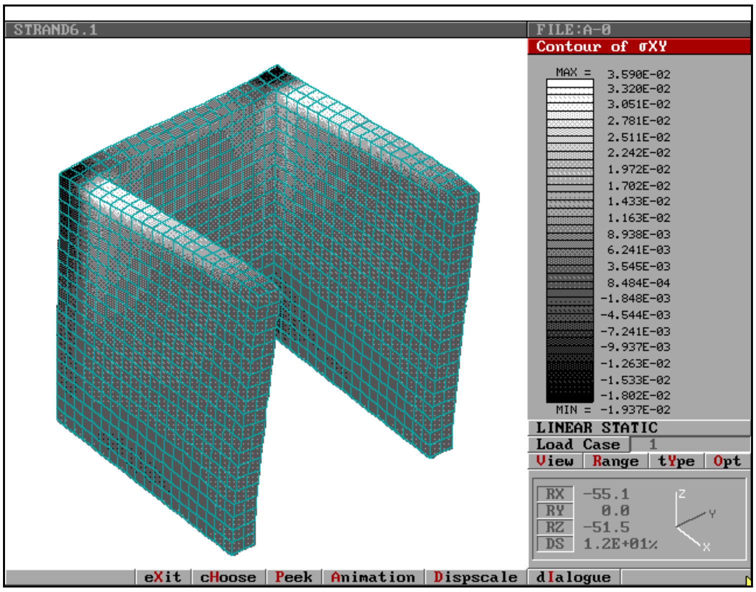

Fig. 6 Distribution of s_{xy} stresses on deformed shape

sonry structure with gridwork on the top (a–3) location of the maximum stress values can be found in the middle of the height but around the same parts in horizontal sense as before (Fig. 7). When wall-openings are considered (b–0,1,2 and 3), location of the highest stresses are concentrated around those openings.

The displacement results d_y, also shown in Tab. 1, are related to maximum values of that on external side of the farther "weak" wall in the direction of loading action (axis y). On the basis of displacement reductions concerned to the serviceability performance the following order of effectiveness can be set up: vertical tie strengthening, horizontal tie refurbishment and, providing the so-called box-like behaviour under horizontal loads, the roof steel gridwork at the top as the most effectual refurbishment work in this field.

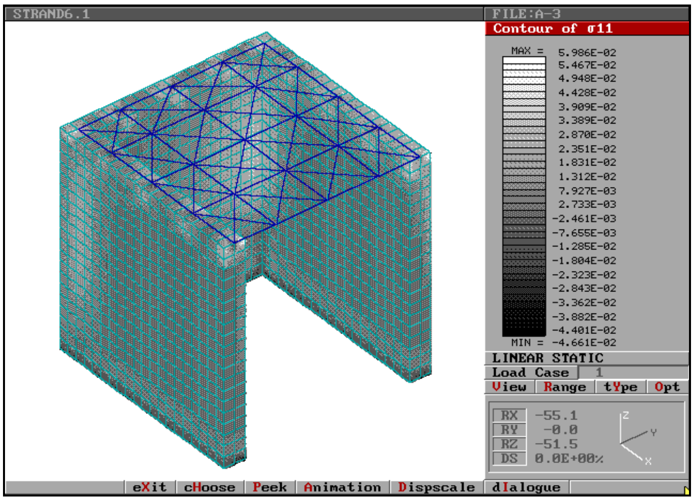

Fig. 7 Distribution of s_{11} stresses on deformed shape

Finally, if quantity of structural steel material used for refurbishment is also taken into account as an economic factor the horizontal tying will probably be the most useful and effective solution unless it is not sufficient from structural point of view. (The weight proportion p[%] of steel material in masonry building is represented in Tab. 1 for each case.)

5. CONCLUSIONS

In this paper the influence of some steel refurbishment methods on masonry box-buildings in the effect of horizontal loads was investigated by means of a finite element analysis program. The conclusions are summarized in Tab. 1, with the most significant numerical results for each case. These values are devoted to justify the siutability of these applications and to compare their effectiveness to one another. According to the obtained results, from structural point of view the steel gridwork fitted to the top of masonry walls seems to be the most effective refurbishment method among the examined cases with regard to considerable reduction of both the stress state and horizontal displacements of masonry construction. On the other hand, using post-tensioned horizontal steel tie-bars inside the masonry walls at floor and/or roof levels, by relatively slight amount of steel material a quite significant reinforcing effect can be easily achieved. Note that in case of particularly high value of horizontal loading applications, such as very strong and severe earthquakes, combination of these refurbishment methods would surely be more effective.

6. FUTURE WORK

At the very end of this paper, it can be finally established that this kind of numerical examination of steel refurbishment techniques appears to be successful and therefore is worth further study. For more sophisticated examination the following progresses can be given to use in the fututre: non-linear static or dynamic analyses; non-linearity of both geometry and masonry material; evaluation of energy dissipation; etc. In this way, calculation and comparison of both ultimate and serviceability performances would be investigated in a far wider range providing more exact results and whereby possibility to choose the most appropriate strengthening solution.

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