13. VULNERABILITY MODELS AND DAMAGE SCENARIOS FOR THE CHURCHES

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13.1 Introduction

Analysis of seismic vulnerability of monumental buildings, and in particular of churches, requires a deeper knowledge and more detailed assessments than those carried out on ordinary buildings; furthermore, if the risk analysis is conducted on an urban scale, an assessment of each individual building is required.

The architectural originality of the churches of the Sicilian Baroque period, and specially of those erected in Catania after the catastrophic earthquake of 1693, and the particular materials used (volcanic rock, calcarenite), have made it necessary to devise new instruments for assessing vulnerability and estimating the expected damage.

The Research Unit of the University of Palermo has worked out a form for the vulnerability field survey that considers the most frequent architectural elements of Sicilian religious architecture, with special consideration for structural aspects and, in particular, for seismic response (Zingone et al. 1999). In the next paragraph the proposed methodology is briefly explained, even though it has not yet been experimented in Catania; however, the layout of the form already represents a result in itself, being available for possible continuation of investigations.

In this phase, the nature of the data made available by the survey carried out by the LSU - Socially Useful Workers (see sect. 7) allowed an assessment of vulnerability for the church facade alone; the simple mechanical model proposed in the next paragraphs is in fact based on a reduced number of parameters, obtainable from the photographs and surveys attached to the LSU form. The facade is certainly the most important macroelement in a seismic risk analysis for churches, because:

- the facade is one of the most vulnerable macroelements, especially with respect to overturning mechanisms; the moderate cracking situations produced in Catania by historic earthquakes are concentrated exactly in the zones of connection with the rest of the building;
- the facades are almost always the only wall that is not restrained, since in Catania the churches are incorporated in the urban fabric; the shear mechanisms are less important, due to the good quality of the Catanese masonry, not only in monumental buildings but also in less important constructions (Liberatore et al. 1999);
- the facades in Catania are characterised by a seismic response substantially independent from the rest of the building; in fact, connection tie bars with the rest of the church were never found and differences in the type of masonry between facade and the other walls produced a limited degree of tying (the facade is often made up of large limestone blocks on the external face, accurately hewn);
- from the point of view of the risk posed to the city, the facade represents a critical element for danger of collapse on public spaces; furthermore these facades are

almost always of large dimensions, usually higher than the structure behind (sail peak), and include great cornices, statues and other decorative elements.

13.2 Overall vulnerability of churches through an analysis by microelements: proposal of a new form

Vulnerability estimation for structures can be performed after processing the data collected through survey forms. Generally the structural geometry and the mechanical features of the materials are required in order to formulate a vulnerability assessment. Obviously, special structures need appropriate forms. Referring to the churches, different forms have been drafted in Italy, each of them calibrated on a specific regional context.

A new collecting form has been proposed for churches in Sicily, whereby the structural geometry and the mechanical features of the structural materials are separately investigated. Then the results are combined in order to obtain a vulnerability index included in the range [0,1]. To obtain the vulnerability index, a combination of the scores assigned to the structure according to the entries in the form has to be performed.

After a first investigation on the whole structure, resulting in the attribution of a first-level global vulnerability score, a special investigation for each of the more important elements (macroelements) that constitute the structure is performed. The following macroelements are considered: external walls, internal walls, facade, roof. For each of them, a vulnerability score can be obtained. These scores are combined by means of weighting coefficients, to introduce the influence of each of them in the seismic response or in the global collapse, so that a second-level global vulnerability index can be obtained.

By comparing this result to the outcome of first level investigation, a measure of the influence of local collapse on the global collapse is obtained.

13.3 Overturning vulnerability of the facade

By overturning mechanisms we mean collapse situations which are caused by the rotation of whole masonry portions due to loss of equilibrium due to seismic actions orthogonal to the facade. These situations are possible if the masonry remains to a certain extend monolithic, a fact that certainly occurs for the facades with square ashlars of the churches of Catania, otherwise there would be premature local collapse due to crushing.

Therefore, if the element can be considered as a rigid body it is possible to define two distinct limit states with regard to the seismic action for this mechanism, namely: a) activation of oscillation (*damage limit state*); b) complete overturning (*collapse limit state*).

The former is found when the conditions of static equilibrium are lost in the course of seismic excitation acting at the base, considering in this assessment the stabilising effect given by the weight of the macroelement and the horizontal inertial forces, proportional to the masses through a multiplier λ. Assuming the body as rigid, this multiplier represents the acceleration of drag at the base; in reality, by virtue of the dynamic amplification the multiplier would more correctly be the ordinate of the response spectrum (in g units), but other factors are instead on the safe side, such as a light tying between walls. Therefore, if the maximum acceleration of the ground reaches the value λ, the facade begins to oscillate, detaching itself from the walls of the nave and thus giving rise to the formation of cracks (*damage limit state*).

With the onset of oscillations, the dynamic equilibrium of the wall is still possible, even in the presence of further increases of the base motion, the seismic action being a sequence of alternating impulses. The correct response may be assessed only through a dynamic non-linear analysis; even if one wants to treat the problem in an approximate form, it is no longer possible to refer to the forces. It is in fact necessary to consider the displacement response spectrum, and in particular the maximum ground displacement (asymptotic spectral value for large periods), because the time that a block takes to complete a cycle increases with the excursion. A limit value is given by the displacement that brings the projection of the centre of gravity of the overturning body just outside its supporting base. In this case, a situation that results unstable in static conditions is found (the wall in that limit configuration, without initial velocity, overturns rather than returning gradually to the initial position). Therefore it can a displacement equal to half of the useful arm of the weights can be assumed, with due caution, as a *collapse limit state* in dynamic condition.

The problem of calculating the vulnerability is therefore traced back to the assessment of the two geometric parameters of the facade, linked to the shape and to the distribution of the masses. These parameters are the collapse multiplier λ, representative of the damage limit state, and the useful arm of the weights δ, necessary for checking the collapse limit state. Therefore, this approach disregards the masonry quality; Giuffrè (1993) showed, both theoretically and experimentally, that a lack of transversal monolithicness means activation of the mechanism for lower values of the seismic multiplier. Indeed, carrying out an overturning check around the external corner corresponds to accepting a stress state of infinite compression. One possibility to bring back a problem of resistance to geometric terms is that of setting the hinge back relative to the outside edge. Indicating by χ the ratio between this setback and the thickness of the wall, for the buildings of Ortigia, Giuffrè proposed to consider values equal to 0.05 or 0.1, depending on masonry quality. If the base cross-section is rectangular, the parameter χ is directly linked to the ratio α between the maximum stress on the outside edge and the average stress, due to the effect of the weights (α=2/3χ): values of α equal to 13.3 and 6.7 correspond respectively to the two indications of Giuffrè for χ.

In the case of concave or convex facades, typical in the churches of Catania, the shift of the hinge by a factor χ does not have any physical meaning. It is in this case better to refer to the parameter α, that is to consider a compressive stress increment as limit state. In fact, it may be considered that the designers of the past dimensioned the facade by implicitly assuming a certain factor of safety for material, while for the overturning equilibrium conditions it is reasonable to make reference to the limit crushing strength. In this way it is possible to check plans of different type, always referring only to geometrical parameters and, possibly, to an assessment of the quality of the masonry.

13.3.1 *The vulnerability model of the facade*

A geometric model that permits description through a limited number of parameters was devised for the types of facade in Catania (Fig.13.1), with reference to the cross-section in plan and the shape of the elevation. In particular, in addition to the general dimensions of the facade (width, height and thickness of the various parts) and the main openings (portal; rose window; another couple of symmetric openings, wherever placed), the external pilasters are considered, defined by the overall width b_e, the depth s_e, the height h_e (in the cases of facades with columns, half-columns or with pilasters of different dimensions, equivalent parameter values, with regard to weight and inertia, must be attributed). Furthermore, internal pilasters are considered, in order to simulate the effect of the portions of lateral walls that are tied to the facade and, obviously, have a stabilising effect.

For what concerns the different types of front of the church, the model, which in the case of figure 13.1 corresponds to the protruding facade (Fig.7.4), manages to consider them all, that is: 1 - triangular facade ($b_s=b_f$; $h_l=h_f$; $h_s=0$); 3 - rectangular facade ($h_l=h_f$; $h_s=0$; $h_t=0$); 4 - rectangular facade with gable ($h_i=h_f$; $h_s=0$). In the case of facades with rectilinear cross-section, formulas were worked out that analytically supply the values of the two indicators of vulnerability (λ and δ) as a function of the geometrical parameters of the facade (Cocina et al. 1999). This model of vulnerability has been applied to 34 of the 70 churches of Catania, surveyed by the LSU Project. The graphic survey documentation attached to the form allowed for determination of the main dimensions of the facade (width, height, thickness); the enormous number of photographs available were also used to obtain the other dimensions (openings, pilasters etc.) with a certain accuracy, through photographic straightening.

The examined churches are shown in Table 13.1, that draws up a list of: the type of church (plan and type of facade - see Figs.7.3-4), the volume V, the average compression stress σ (assuming ρ=2000 kg/m^3), the multiplier λ and the stabilising arm of the weights δ, the last ones assessed with respect to the external edge of the base cross-section. The table also shows the values of λ and δ obtained considering the strength of the masonry, which is generally of good quality in Catania (α=13.3); these are to be compared with the input used in other parts of the Project (Faccioli et al. 1999). Via GIS, we have obtained for the site of each church the peak accelerations (PGA) estimated for both scenario earthquakes (see sect. 3), and the value of the displacement spectrum S estimated for a period equal to 2 s, relative to the level I (1693-type event) scenario earthquake. The latter value has been obtained by doubling the spectral displacement value for T=1 s, since the displacement spectrum is approximately linear with period up to 2 s (Faccioli et al. 1998).

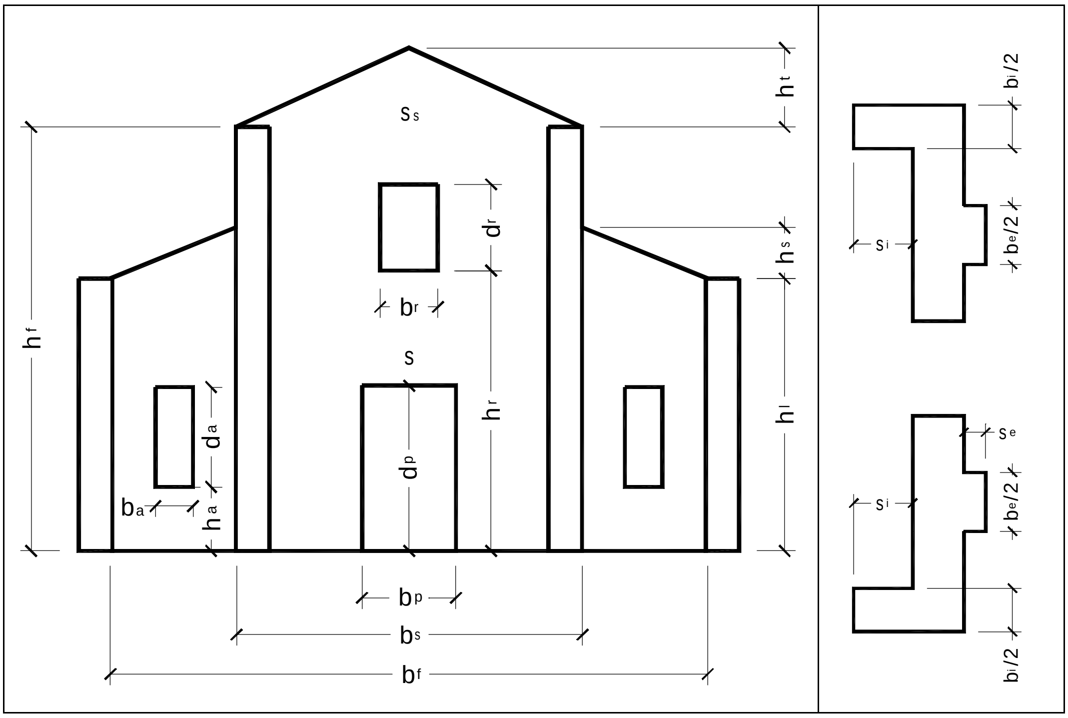

Figure 13.1: Geometrical parameters of the facade model, in elevation and plan.

It can be noted that the churches in which large pilasters or columns are present, generally those of greater architectural value, show the lowest vulnerability; even considering the masonry strength, the values of the multiplier in the largest churches are around 0.2. Furthermore, it can be observed that the average compression stress due to permanent loads is equal to 0.3 MPa on average; this means that for the assumed quality of masonry (α=13.3), a crushing resistance of 4 MPa is assumed, to be considered correct in Catania.

The complexity of the Baroque facades in the churches of Catania has made it necessary, in some cases, to use a more accurate geometric model for the definition of all the significant volumes (friezes, cornices, openings etc.), also in order to check the reliability of the simplified model. As an example, figure 13.2 shows the CAD model and the results obtained for the church of S. Francesco Borgia (protruding facade with columns), which are comparable with those supplied by the proposed vulnerability model (Table 13.1).

Table 13.1: Vulnerability in terms of damage and collapse limit states for facades.

Church	nave	type	V (m^3)	σ (Mpa)	λ	δ (m)	α=13.3		PGA	PGA	S (1s)	f
							λ	δ	level II	level I	level I	
S. Vito	1	2-A2	73	0.31	0.07	0.53	0.05	0.38	0.20	0.30	0.28	0.7
S. Agata la Vetere	1	1-A2	565	0.52	0.07	0.78	0.06	0.67	0.20	0.30	0.23	1.5
S. Maria della Mecca	1	3-A1	103	0.29	0.08	0.54	0.07	0.47	0.18	0.28	0.22	1.1
S. Francesco da Paola	1	1-A3	208	0.34	0.11	0.90	0.08	0.66	0.18	0.28	0.17	1.9
S. Marta	1	1-A2	113	0.27	0.11	0.69	0.08	0.50	0.18	0.30	0.28	0.9
SS.Angeli Custodi	1	1-A2	151	0.30	0.11	0.76	0.09	0.62	0.16	0.27	0.16	1.9
SS.Sacramento-Borgo	1	1-A2	190	0.34	0.11	0.88	0.09	0.72	0.19	0.29	0.23	1.6
SS. Cuore di Gesù	1	4-A2	310	0.47	0.12	1.13	0.10	0.94	0.18	0.30	0.21	2.2
S. Michele Minore	1	4-A2	113	0.29	0.12	0.80	0.11	0.74	0.18	0.27	0.16	2.3
SS.Antonio ed Euplio	1	1-A1	42	0.16	0.13	0.62	0.11	0.53	0.16	0.27	0.16	1.7
S.Giuseppe al Duomo	1	1-A2	159	0.29	0.13	0.87	0.11	0.74	0.18	0.30	0.23	1.6
S. Maria del Carmelo	1	1-A1	67	0.20	0.12	0.56	0.11	0.52	0.18	0.28	0.17	1.5
S. Maria dell'Aiuto	1	2-A3	450	0.40	0.13	1.22	0.11	1.03	0.16	0.27	0.16	3.2
S. Orsola	1	1-A3	96	0.22	0.15	0.80	0.11	0.58	0.18	0.28	0.16	1.8
S. Berillo	1	1-A1	60	0.25	0.14	0.78	0.12	0.67	0.18	0.29	0.17	2.0
S.Maria Consolazione	1	1-A2	75	0.22	0.15	0.78	0.12	0.62	0.20	0.30	0.28	1.1
S. Agrippina	1	3-A2	65	0.20	0.15	0.72	0.12	0.58	0.16	0.27	0.16	1.8
S. Agostino	1	4-A3	184	0.27	0.15	1.04	0.13	0.90	0.20	0.30	0.22	2.0
SS. Bambino	1	1-A2	69	0.25	0.15	0.89	0.13	0.77	0.20	0.30	0.28	1.4
S.Gaetano alla Marina	1	1-A1	243	0.32	0.14	0.99	0.13	0.92	0.18	0.27	0.17	2.7
S.Francesco (cappuc.)	1	1-A2	68	0.21	0.17	0.85	0.13	0.65	0.16	0.29	0.27	1.2
Sacro Cuore al Fortino	C	1-A1	147	0.30	0.16	1.06	0.14	0.92	0.16	0.28	0.21	2.2
S.Cristoforo alle Sciare	1	1-A2	126	0.27	0.18	1.13	0.15	0.95	0.16	0.28	0.21	2.3
S.Maria diMonserrato	1	1-A2	148	0.25	0.19	1.06	0.16	0.90	0.19	0.29	0.23	2.0
S. Maria della Palma	1	1-A2	139	0.21	0.20	1.00	0.16	0.80	0.16	0.26	0.16	2.5
S. Sebastiano	1	3-A2	81	0.22	0.19	1.03	0.16	0.86	0.18	0.27	0.17	2.5
S. Maria di Gesù	1	1-A1	74	0.21	0.18	0.79	0.17	0.75	0.18	0.30	0.22	1.7
S. Benedetto	1	1-A2	1362	0.45	0.22	2.35	0.17	1.82	0.18	0.30	0.23	4.0
S. Francesco Borgia	3	2-A3	870	0.46	0.21	2.42	0.18	2.07	0.18	0.30	0.23	4.5
SS.Cosma e Damiano	1	1-A2	165	0.18	0.24	1.27	0.19	1.01	0.16	0.30	0.22	2.3
S. Anna	1	1-A2	109	0.26	0.22	1.32	0.19	1.14	0.17	0.29	0.22	2.6
S. Domenico	1	4-A2	704	0.41	0.24	2.40	0.20	2.00	0.20	0.30	0.28	3.6
S. Biagio	1	3-A3	676	0.33	0.27	2.03	0.22	1.65	0.20	0.30	0.23	3.6
SS. Sacramento	1	1-A2	225	0.30	0.27	1.76	0.23	1.50	0.20	0.28	0.16	4.7

13.4 The damage scenario

The damage scenario due to overturning of the facade is obtained by comparing, in Table 13.1, the vulnerability and the scenario seismic excitation, expressed through PGA, with reference to both the damage and the collapse limit states. Onset of overturning (*damage limit state*) occurs when the PGA exceeds the static collapse multiplier λ; in this case it can be seen that, already for the level II scenario earthquake (1818-like event), most of the churches should suffer considerable damage. In the case of the level I scenario earthquake, all the facades would obviously tend to detach themselves from the rest of the building (*damage limit state*); however, collapse seems to occur only in two cases (shaded in column δ of Table 14.1). The last column shows the safety factor f with regard to the *collapse limit state*; besides the two churches that would collapse, for other six churches the safety margin is rather small (f<1.5).

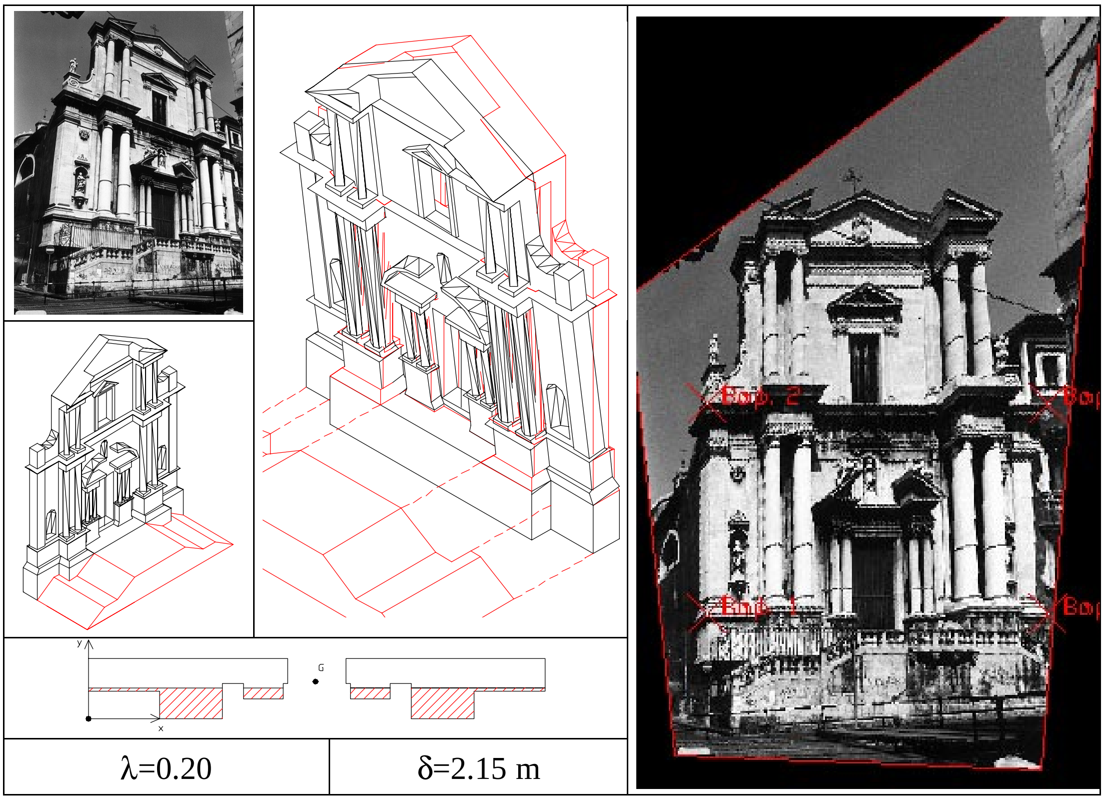

Figure 13.2: Church of S. Francesco Borgia: photo straightened, solid model, base section.

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