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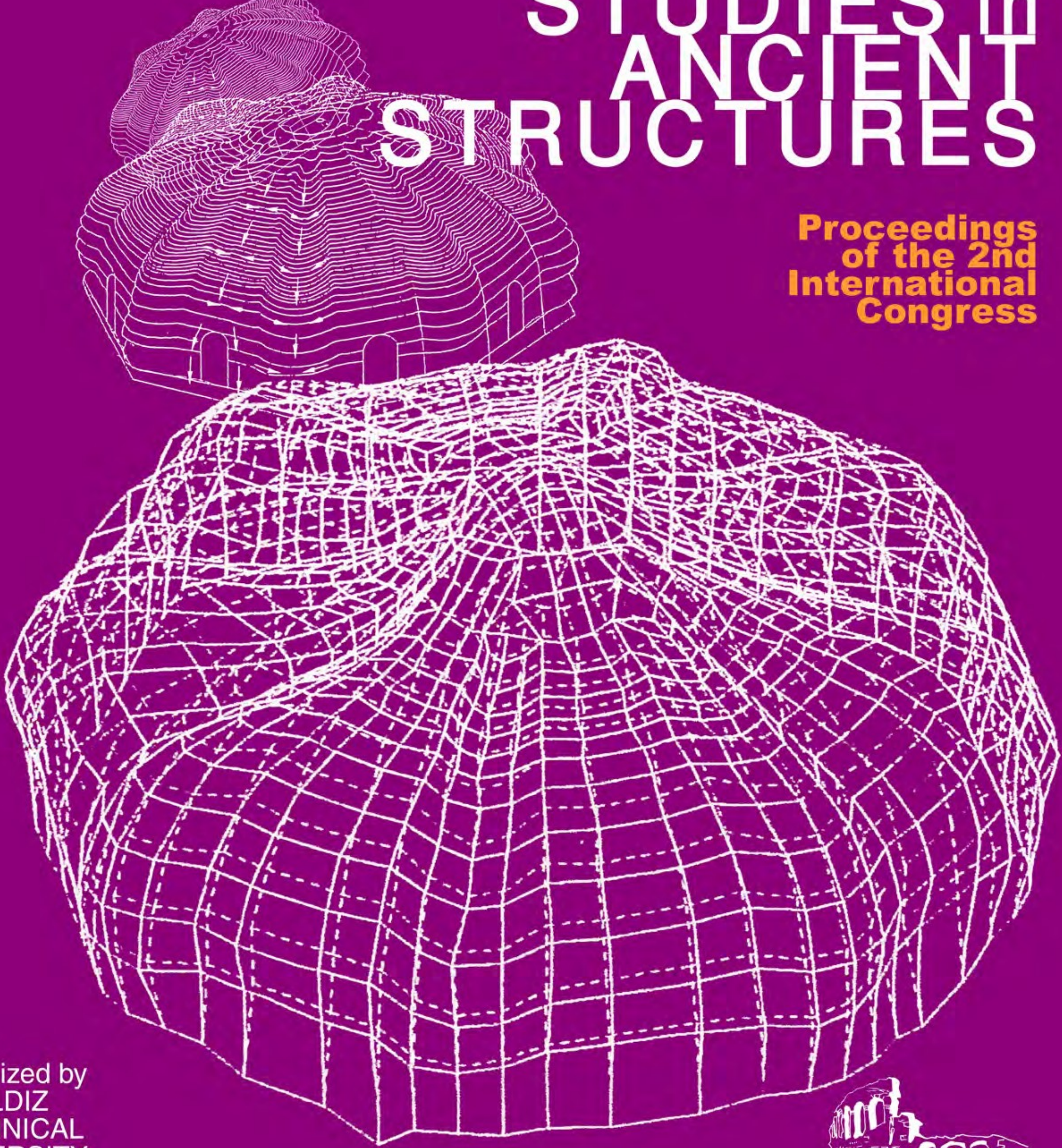

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ANALYSES OF SEISMIC RELIABILITY OF THE MASONRY CONSTRUCTIONS BUILT ON THE DIOCLETIAN'S PALACE IN SPLIT (CROATIA)

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ABSTRACT

An automatic procedure of relief usually carried out to evaluate the seismic vulnerability of masonry buildings has been improved and applied to structural aggregates built up, in many ages, in the Palace of Roman Emperor Diocletian, in Split (Croatia), between the forth century a.C. and the nineteenth century, which represent a extraordinary historical testimony of the town.

1. INTRODUCTION

In the procedures of analysis of the seismic vulnerability of the masonry buildings, according to the methodologies running employed in Italy, the relief operations on one side constitute the more onerous operating phase from the point of view of the necessary time and the economic costs, from the other the more difficult and delicate phase from the point of view of the reliability of the successive evaluation of vulnerability. Handbook and predisposed technical forms for such relieves constitute profits guides, but, in particular if used from detectors not particularly expert, can carry to wrong or not reliable classifications in the rigid outlines of the prefixed categories from the analysis methodologies. Categories that often do not concur to hold account of the enormous variety of the masonry walls typologies, floors and roofs realised in different zones and/or different periods, and of the same ambiguity of the terminology employed for their description.
In the within of the construction of an expert system for the analysis of seismic vulnerability of buildings in masonry, they have been put to point computer science procedures that concur the interactive access of the detector with bases of acquaintance and bases of data, orienting the observation of building the more important characteristics of the typology in examination and automatically

recording the result in the format demanded for the further analyses of vulnerability.
The relief procedure and the corresponding analysis of vulnerability, in this phase, has interested a champion of 63 masonry buildings, pertaining to zones south-east of the Diocletian's Palace, in the town of Split (Croatia) (Fig. 1-6).
Several in-situ tests have been carried out on different masonry walls, with different typologies (from the Diocletian's walls of the 4-th century, to 8-th century ones, to medieval ones, until 19-th century ones (Fig. 7)) in order to calibrate the use of the expert system and to became possible the evaluations of structural reliability and the forecast of the effects of different hypotheses of retrofitting.

2. VULNERABILITY ANALYSES

The procedure, created in Padova University [8-15] is based on a vulnerability model of masonry buildings, that depend on the following parameters:
I1 is the ratio of in-plane shear strength of the walls system to total weight;
I2 is the ratio of out-of-plane flexural strength of the most critical external wall to total weight, evaluated by summing the resistance of vertical (I2') and horizontal (I2'') strips;
I3 is the weighted sum of the scores of seven partial vulnerability factors;
a is the mean absolute acceleration response of the building;
u is the uncertainty factor depending through a fuzzy relation on I3.

The output vulnerability Vu = f (I1, I2, a, u) is the probability of collapse or damage [illegible]degree D4 (EMS98: European Macro-seismic Scale 1998).
The evaluation of the vulnerability of each building requires the definition of rules to merge qualitative and quantitative informations. Two aspects must be solved: the relation between I3, synthesising qualitative judgements on the characteristics of the building and the parameter u (of which the reliability function f_S = 1-Vu depends); the influence of the quality of informations on the final measure of f_S.
The fuzzy set theory [30, 32] has been adopted for such purposes: it gives general formal rules to treat vague informations which have been already applied in the field of structural reliability. Details of the procedure are given in [8] and the results can be given, for each value of the seismic intensity a, and for each building, through the membership function of the fuzzy subset of interval of variation of f_S.
The building can be assigned to fixed classes of vulnerability using numerical techniques for ordered classification of the fuzzy subset fs. In the application five classes of vulnerability (Very Small, Small, Medium, Large, Very Large) to which the fuzzy subsets are associated, are considered.
The results can be used not only to compare the vulnerability of every single building of a group (Vu) but also the vulnerability of different groups of buildings

(Vg); in the second case the statistical distribution of the buildings of a sample in the classes can be used. Both the types of comparison are useful when retrofitting interventions are to be planned in a region, given for every group of buildings the expected intensity of the seismic action.
Shaking table tests on masonry buildings models [3] show that in the highly damaged state the seismic intensity a is nearly equal to PGA.

To the current state the complex is introduced like a altogether apparently homogenous take-over for constructive typology. In the truth, in phase of relief, above all from the examination of the inner surfaces of masonry, they have been found, in a great number of cases, situations of walls with various masonry types much in the same wall (Fig. 8), with insertions of far ages much between they, from the Roman Diocletian's wall, of IV the century, to the clay bricks wall of VIII the century to the medieval, until renaissance, baroque and finally twentieth-century examples. The prevailing use of the squared or roughly hewn stones, arranged in regular way in all the facades, can draw in deceit on the real distribution of the mechanical characteristics of the carrying elements. The presence of a second poorer quality and more worse organised inner layer, let alone the frequent presence of a internal zone of material with insufficient consistency, even if modest thickness, alters the theoretical carrying capacity considerably, is for forces in the plane of the wall (compression for vertical loads, shear for horizontal actions) that for those out of plane.
To completion of the general information on the characteristics of the built up complex, it goes added that the buildings are developed with articulated aggregations a lot in plant and often also in elevation and denounce various states of conservation, prevailing one be of generally poor maintenance. The expert system has concurred variable times of relief from one - two hours for simple buildings to three - four hours for buildings with articulated plant.
The masonries are realised mostly in quasi-regular fabric squared or roughly hewn stones of good quality (Fig. 9-10), of limestone origin; the original mortar of aerial lime is rather porous and has medium resistance to the superficial abrasion. The state of conservation of the same one is extremely variable, like often happens in the historical centres, depending mostly on the state of exposure and maintenance of the masonry surface. In the zones of insufficient maintenance and with high humidity degree the mortar turns out nearly always of much poor quality.
In attended of further experimental results, in the treatment of the data they have been assumed temporarily, for the materials, values that for affinity with previous surveys of the search unit, correspond to three different levels of mechanical characteristics of masonry (in the order: compression strengths = 2.00, 3.00, 4.00 MPa; tensile strengths = 0.10, 0.15, 0.20 MPa; density = 2300, 2500, 1800 kg/m^3).
The analysis of seismic vulnerability of the single buildings, conduct with fuzzy approach is carried out for increasing values of seismic intensity, measured from

the medium value of the response acceleration of the building, between 0.08g and 0.40g. Tale field comprises, for a reason or purpose pure indicative, also values 0.16 g, 0.28 g and 0.40 g, suggested from the Italian Code for the verification of masonry buildings of new construction respectively in zones of third, second and first category. The vulnerability is measured through a qualitative judgement to 5 levels: Very Small, Small, Medium, Large and Very Large. In Fig.11 are brought back the classes of vulnerability of the single examined buildings, for increasing values of answer acceleration (0.08 g, 0.12 g, 0.16 g, 0.28 g, 0.40 g), and for a medium value of the "class of uncertainty ", for every building. In a detailed report of next publication the analyses of vulnerability of the single buildings related with the data of II level GNDT forms will be introduced also.

3. CONCLUSIONS

The judgements on the seismic vulnerability of each building, also being born from analysis of collapse mechanisms connected to horizontal actions, can naturally be correlated with the state of static efficiency, and in last analysis with the reliability of the same construction also under current conditions. In other words, the poor resistance to the horizontal actions, that it is involved the operation of the resistant walls is for shear that (above all) for bending - due to a poor control of the horizontal structures (possibility of slip of the wooden rafters of floors), to the lack (also partial) of perimeter r.c. beams or iron chains - reveals a inborn weakness of the whole construction. One elevated vulnerability class can indicate therefore also, plus generally, one greater dangerousness of the state of the construction. The vulnerability maps can therefore be one qualitative instrument for the appraisal of the "state" of an aggregate of buildings.

At the current state of the research, in the vulnerability analyses have been used values of the mechanical characteristics of masonry deduced for analogy from previous experiences, mediated through the interpretation of the tests carried out in situ. In extending and detailing relationship, currently in preparation, analyses of different carried out vulnerabilities placing to comparison will be exposed also hypothesis on the materials, considering also the cases in which interventions of consolidation of masonry and of buildings in their complex are operated (insertion of chains, formation of perimeter beams, etc), let alone the forecasts of damage for every building, for several scenarios of seismic intensity. In both these analyses, lead with the aid of the expert system previously cited, will distinguish also the "relative classes of uncertainty " to every building, described like fuzzy sets through the information deduced from the compilation of II level GNDT forms.

Returning to the description of the activities of the unit of research of Padova University, it goes remembered that the survey team has carried out between April and May 2000 the collection of the necessary information (carrying relief of geometry, elements, floors, materials, cracks, degree of conservation, etc.) on a

total of 63 buildings (23 in zone 5 and 40 in zone 10) in correspondence of the wall south of the Diocletian's Palace.
In attended of one more deepened and careful appraisal of result of tests carried out in some buildings, that it will constitute the base for the analyses of vulnerabilities included in a detailed report that the unit of research is preparing, remain temporarily acceptable the choices operated previously (and prudently) for analogy with previous experiences. Otherwise, the adopted fuzzy approach for the expert system is particularly adapted to the treatment of "uncertain" informations, as they are those on the mechanical characteristics of the materials and/or on the resistances of the structural elements.
It is intention of the group of research, in accordance with the municipality of Split, to extend the relief and the analyses of seismic vulnerability also to the buildings of the other zones contained in the perimeter of the Diocletian's Palace.

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REFERENCES

1. Arezzo, P., Bernardini, A., Gori, R., Muneratti, E., Paggiarin, C., Parisi, O., and Zuccaro, G. 2000, "Vulnerability and probability of collapse for classes of masonry buildings", in *The Catania Project. Earthquake damage scenarios for a high risk area in the Mediterranea,* (E. Faccioli and V. Pessina editors), pp. 146-156, GNDT, Roma.
2. Benedetti, D., Petrini, V. 1984, "Sulla vulnerabilità sismica di edifici in muratura: un metodo di valutazione", *L'Industria delle Costruzioni*, n. 149.
3. Benedetti, D. and Pezzoli, P. 1996, "Shaking table tests on masonry buildings. Results and comments", ISMES, Bergamo.
4. Beria, R., Bernardini, A., Gori, R., Modena, C. 1993, "Rilievi assistiti da calcolatore dell'edilizia muraria per valutazioni di vulnerabilità sismica", *6° Conv. Naz. L'Ingegneria sismica in Italia*, Perugia.
5. Bernardini, A., Gori, R., Modena, C. 1988, "Verso un sistema esperto per analisi di vulnerabilità sismica di singoli o di gruppi di edifici in muratura", *Report ISTC*, RI-3/88, Istituto di Scienza e Tecnica delle Costruzioni, Università di Padova.

Fig.1 - Aerial view of Diocletian’s Palace in Split

Fig. 2 - View of a part of the south-west wall of Diocletian’s Palace

Fig.3 - View of east wall of Diocletian's Palace

Fig.4 - View of south quarter of Diocletian's Palace

Fig.5 - View of south-west quarter of Diocletian's Palace

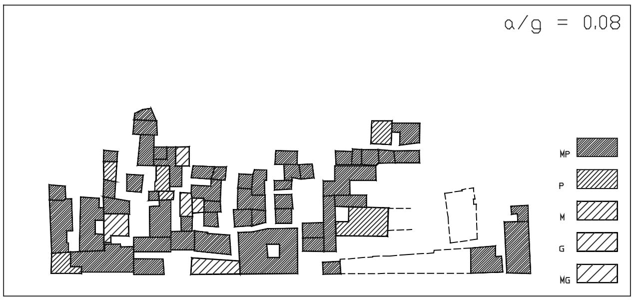
Fig.6 - View of two masonry buildings of south-east corner of Diocletian's Palace

Fig.7 - Construction periods of masonry buildings of Historic Core of Split

Fig.8 - Wall with inserts of Diocletian's masonry

Fig.9 -


Fig.10 -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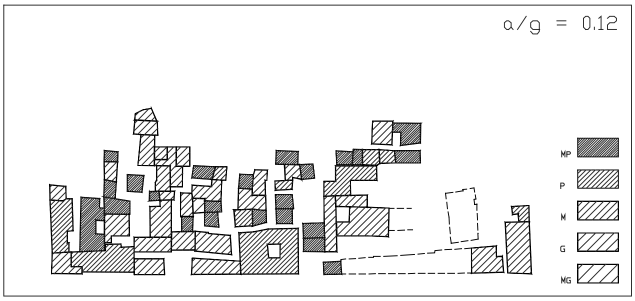
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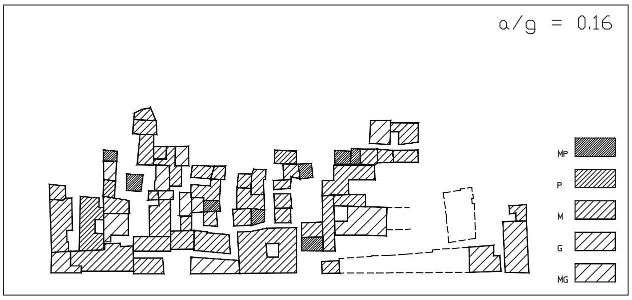
a/g = 0.16
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Fig. 11 – Vulnerability classes for south Diocletian's Palace masonry buildings (Five classes, from Very Small (MP) to Very Large (MG)) [25].

6. Bernardini, A., Gori, R., Modena, C. 1988, "Valutazioni di resistenza di nuclei di edifici in muratura per analisi di vulnerabilità sismica", *Report ISTC,* RI-2/88, Istituto di Scienza e Tecnica delle Costruzioni, Università di Padova.
7. Bernardini, A., Gori, R., Modena, C. 1989, "Previsioni di Danno di Edifici in Muratura sotto Azione Sismica", *Report ISTC*, RI-4/89, Istituto di Scienza e Tecnica delle costruzioni, Università di Padova.
8. Bernardini, A., Gori, R., Modena, C. 1990, "Application of coupled analytical models and experential knowledge to seismic vulnerability analyses of masonry buildings", in *Earthquake damage evaluation & vulnerability analysis of building structures* (A. Koridze editor), Omega Scient., Oxon, U.K..
9. Bernardini, A., Gori, R., Modena, C. 1990, "Vulnerabilità di Tipologie Edilizie in Muratura e C.A.", *Atti del Convegno del Gruppo Nazionale per la Difesa dai Terremoti, CNR*, Pisa.
10. Bernardini, A., Gori, R. and Modena, C. 1990, "A Structural Model for Continuos Masonry Systems in Historical Centres", *Structural Conservation of Stone Masonry,* Proceed. of the Intern. Conf. held in Athens, ICCROM, Rome.
11. Bernardini, A., Gori, R., Modena, C. 1990, "A Theoretical Model for Seismic Damage Forecasting of Masonry Buildings", *Proceedings 9th Europ. Conf. on Earthquake Engineering*, Moscow.
12. Bernardini, A., Gori, R., Modena C. 1991, "A Knowledge based Methodology for A-Priori Estimates of Earthquake Induced Economical Losses in Old Urban Nuclei", Proc. of CERRA-ICASP6, *Sixth Int. Conf. on Applications of Statistics and Probability in Civil Engineering*, Mexico City.
13. Bernardini, A., Gori, R., Modena, C. 1991, "Un sistema esperto per la previsione del danneggiamento sismico degli edifici in muratura", *5° Convegno "L'Ingegneria sismica in Italia"*, Palermo.
14. Bernardini, A., Gori, R., Modena, C. 1992, "Fuzzy measures in the knowledge based diagnosis of seismic vulnerability of masonry buildings", *Probabilistic Mechanics and Structural and Geotechnical Reliability* (J.K. Lin editor), Proceedings of Sixth Speciality Conference held in Denver, Colorado, July 8-10, 1992, ASCE, New York.
15. Bernardini, A., Gori, R., Modena, C. 1992, "A knowledge based survey of masonry buildings for seismic vulnerability evaluations", *Cahiers du Centre Européen de Géodynamique et de Séismologie,* Vol. 6, Proc. Workshop Application of Artificial Intelligence, Techniques in Seismology and Engineering Seismology, Walferdange, Ed. Zonno & Ducarme, Impr. J. Beffort, Luxembourg.
16. Binda, L., Mirabella, L., Roberti, G., Abbaneo, S. 1994, "Il progetto delle indagini per la diagnosi strutturale", *Seminario su "Evoluzione nella sperimentazione per le costruzioni"*, Merano.
17. Calzuola, F. 1984, *Sisto Mastrodicasa Scritti e lavori, Fondamenti tecnici della fatiscenza muraria*, Benucci ed., Perugia.
18. Ceradini, V., Giuffrè, A. 1988, "Vulnerabilità e conservazione nel quartiere della Graziella in Ortigia", *Atti 5° Convegno Nazionale "L'Ingeneria sismica in Italia"*, Palermo, 1991, pp. 139-158.

19. CNR/GNDT, Regioni Emilia Romagna/Toscana 1986, "Istruzioni per la compilazione della scheda di rilevamento, esposizione e vulnerabilità sismica degli edifici", Litografia della Giunta Regionale, Firenze.
20. Egerman, R. 1997, "On the load bearing capacity of natural stone buildings. Inspection, recorsing, measuring methods", *Inspection and Monitoring of the Architecturale Heritage*, International Colloquium Seriate.
21. Ferić, K., Rak, Z., Domazet, A., Akrap, N. 2000, "Report on Constructive Materials Testing Historical Centre of Split", Civil Engineering Institute of Croatia, Split.
22. Forde, M.C. 1992, "Non destructive testing of masonry", *Proc. 2nd Int. Conf. on Nondestructive Testing of Civil Structures and Materials*, University of Colorado, Boulder, Colorado.
23. Gavarini, C. 1987, "Ipotesi per una nuova scala di vulnerabilità sismica degli edifici in muratura", *Atti del 3° Convegno "L'ingegneria sismica in Italia"*, Roma.
24. Giuliano, M., Gori, R., Sáez, S. 2000, "Estudio de Vulnerabilidad Sísmica de Viviendas de Adobe en la zona de Coelemu (8ª Región, Chile)", *Jornadas Sudamericanas de Ingenieria Estructural*, Punta del Este, Uruguay.
25. Gori, R., Paggiarin, C., Muneratti, E. 2000, "Il Palazzo di Diocleziano in Spalato: Analisi della vulnerabilità sismica degli edifici in muratura della zona sud", *Convegno di Studi: La Tutela del Patrimonio Architettonico nel Bacino del Mediterraneo*, *Incontro di studio: La ricostruzione del quadrante sud-est del centro storico di Spalato all'interno del Palazzo di Diocleziano,* Politecnico di Bari, 26-27 maggio 2000, *Argomenti di Restauro della Facoltà di Architettura del Politecnico di Bari*, n.2, Bari.
26. Modena, C., Bernardini, A., Gori, R. 1988, "A Research on the Seismic Vulnerability of Existing Masonry Buildings", *Proceedings of CIB W23 - Wall Structures*, Austin, Texas, U.S.A..
27. *NEXPERT Object, Version 2.0, User's guide 1991*, Neuron Data, Palo Alto, California, U.S.A.
28. Noland, J.L., Kingsley, G.R. 1986, "Work in progress on nondestructive evaluation of masonry structures", Interim Report of the Joint USA-Italy Workshop, Milano.
29. Rossi, P.P. 1993, "L'impiego dei martinetti piatti nello studio delle murature", in *Atti del seminario "Sperimentazione su strutture, Attualità ed affidabilità delle metodologie di indagine"*, Venezia.
30. Zadeh, L.A. 1973, "Outline of a new approach of the analysis of complex systems and decision processes", *IEEE Transactions on Systems, Man and Cybernetics*, **3** (1)
31. Zaninetti, A. 1993, "Tomografia sonica", *Atti del seminario "Sperimentazione su strutture. Attualità ed affidabilità delle metodologie di indagine"*, Venezia.
32. Zimmermann, H. J. 1987, *Fuzzy sets, decision making and expert systems*, Kluwer Ac. Pub., Boston.