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SEISMIC ASSESSMENT OF HOSPITAL SYSTEMS

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ABSTRACT

An effective reliability-based procedure is presented to assess the capability of an hospital to be functional after a seismic event of given intensity. The hospital is described through its logical scheme and its minimal cut-set representation, then the components failure probability is calculated by FORM and SORM, and finally the system failure probability is obtained in terms of Ditlevsen bounds. The structural response is obtained with 3D linear dynamic analyses, under a seismic input given by the EC8 elastic response spectrum, scaled at a given peak ground acceleration. The strengths of the structural elements are based on design drawings. The method gives helpful indications on the potential sources of damage (structural, non structural, equipment) within the hospital, so that different investment options for its seismic vulnerability mitigation can be evaluated, and retrofitting and rehabilitation criteria can be established. As an example, the evaluation of the probability of failure in terms of service interruption of a case study hospital is presented. Results show that the methods allows for a rational selection of intervention criteria, both in existing structures to be retrofitted, and in the design optimisation of new ones. For the case at hand, some critical problems have been identified, which are related to both structural and non-structural elements and also to the equipment.

KEYWORDS

Hospitals, Assessment, Retrofitting, Upgrading, System Reliability, Functional Collapse, Equipment.

INTRODUCTION

Experiences from past earthquakes have shown that collapse of functional elements (such as X-rays, operating tables, etc.) prevented most hospitals from being fully operative during the post-quake aid operations. Nonetheless, in European seismic codes no specific requirements, apart from those strictly related to structural aspects, are given for non-structural components, piping, equipment and their layout in plan and elevation. Instead, hospitals contain and preserve essential equipment for patient care and for first-aid. Basic supplies like water, electricity, oxygen and communications are needed twenty-four hours a day in order for the hospital to work efficiently without service interruptions that could be fatal. Moreover, equipment such as lifts and litter-lifts, which are essential for assuring internal communications, should always be functioning. It is therefore all too clear that when an earthquakes strikes a hospital, the fact that the main structures have performed well during the seismic event is not sufficient to guarantee the overall efficiency of the hospital.

While Californian and partially Japanese codes specifically address problems related to new hospitals, it is the problem of existing hospitals that has not been satisfactorily solved as yet. In Europe seismic upgrading of existing hospital is a critical challenge, but a rational method to define an intervention strategy to obtain given reliability levels, at least in qualitative terms, has not been set up yet. Besides, target reliabilities for new hospital are exceedingly severe and cannot be applied to existing structures (Nuti 1993).

A first tentative approach to the problem is proposed in the following (Nuti and Monti 1995). The method considers the hospital as a *multi-functional system*, in which the functions are those essential after a seismic event, such as: patient accommodation, diagnostics, x-rays, orthopaedics, dialysis, pharmacy, surgery, first-aid, anti-shock care, catering, etc. Each function is made up of many sub-functions: for instance, if the x-rays machine is located at the first floor, litter-lifts are considered in this case as a sub-function of x-rays. Each sub-function (or sub-component) is assigned a fragility, based both on equipment characteristics and on its location inside the building. It should be clear, for example, that the fragility of a dialysis apparatus changes if it is located at the first or at the fifth floor. Modern system reliability theory allows to evaluate the collapse probability of each function and also to detect the most critical sub-components and to investigate the relative influence of different retrofitting strategies.

The proposed method is then applied to an Italian hospital located in a region, which has undergone in 1984 a degree 7 earthquake (Modified Mercalli Intensity scale).

RELIABILITY OF HOSPITAL SYSTEMS

The steps needed to perform the reliability analysis of an hospital can be outlined as follows:

1. Local seismicity - It should be defined on the basis of analyses on catalogued events, in order to obtain the intensity associated to a given return period. Intensity values are preferably measured in terms of PGA, due to current design specifications;
2. Functional description of the hospital - An accurate analysis of all the functions available in the hospital should be performed, starting from those related to the hospital specialization area and those essential after a seismic event. Each function should then be studied separately;
3. Logical scheme (for each function) - To construct the system logic means to individuate and to connect in a rational sequence, based on their relation to the selected function, all the services whose interruption implies failure of the system. All the services should be localized in plan and elevation, and cooperation to other services should be described in terms of horizontal and vertical paths to be followed within the hospital building. Also, internal communications, usually obtained by means of lifts, and essential equipment for patient survival and for first-aid should be included among the services whose failure is determinant. Basic supplies like water, electricity, communications should always be included as basic services of each function;
4. (Sub-) Components description - Each component (service) should be described as a series system made from sub-components (sub-services), whose failure concurs to its own failure. Strengths and loads of sub-components are described as a vector of random variables, usually defined by means of two-parameter pdf's, with mean and variance conditioned to a given value of an intensity measure (PGA, magnitude, etc.). Correlation can be assigned between different variables. The collapse criterion of each component can be either defined mathematically in closed form or through mechanical models (*e.g.* by a finite element code). This step represent the hardest part of the whole procedure, where the strengths are to be determined through assessment procedures and the loads through structural analyses;
5. Minimal cut-set representation of the system - The minimal cut-set representation of the system can be constructed from the system logic by means of standard methods. While this task can be performed by hand for a reduced number of components, when the number of components increases, the task of finding the minimal cut-set system increases dramatically in complexity and one should resort to specific programs;
6. Iterative analysis of the system with upgrades - Once the system is properly described, the reliability analysis is performed for increasing earthquake intensities. On the basis of the results obtained in terms of global and local probability of failure, the critical components are individuated and retrofit or intervention hypotheses are formulated accordingly.

APPLICATION TO A CASE STUDY HOSPITAL

Description of the hospital

The hospital under consideration is the Castel di Sangro Hospital (Fig. 1), located in the Abruzzi region in Italy. Its construction started in the 50's, with subsequent expansions (the last building was built in 1983), according to increasing demand and funding availability. The total number of beds is 134. The structure consists of 7 r.c. frames buildings designed with the allowable stresses method, according to seismic regulations which required the structures to resist horizontal forces equal to 10% of the vertical load. Design drawings and reports are available

The construction level is that typical of r.c. building at that time, with no detailing concerning shear strength or ductility: *e.g.*, reinforcing steel made from plain bars, distant stirrups, especially in columns, and unreinforced joints. Besides, low-height beams are diffusely used. Partitions are of the conventional type (brick masonry infills) and often contain built-in electric and medical gas lines. Equipments are not anchored. The emergency generator, as is often the case for hospitals, can provide energy to assure functionality of all machines, with the only exception of X-rays.

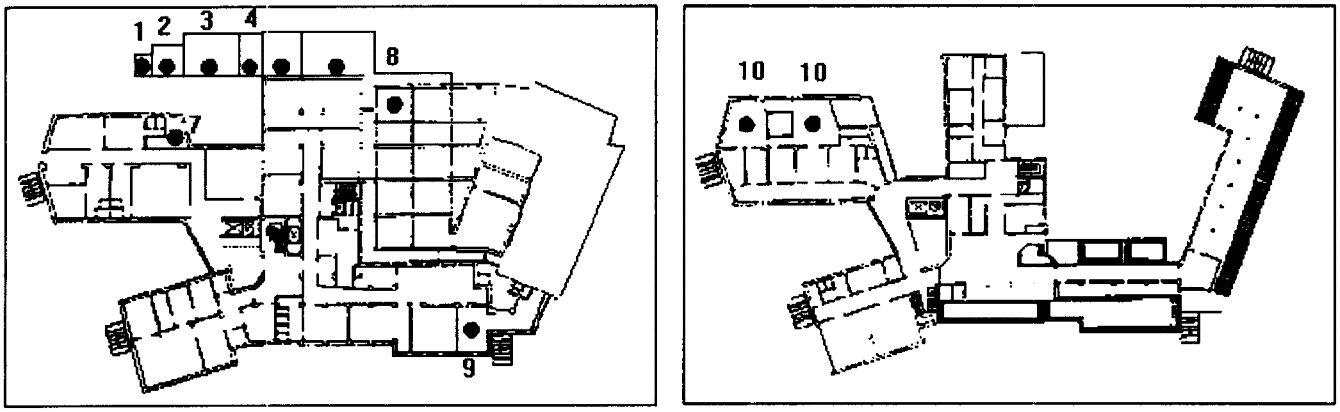

Fig. 1. Hospital plans: basement (left) and 3rd floor (right). Legend: 1- gas tanks, 2- External electric power supply, 3- electric power switch-board, 4- generator unit, 8- water tank, 9- laundry, 10- operating theater, 11- X-rays unit.

Local seismicity

In this century Abruzzi region has been shaken by two destructive earthquakes: the strongest in 1915 having magnitude 6.8 and epicentre in Avezzano, and the other in 1933 with 6.8 magnitude and epicentre in Lama dei Peligni. There have been several earthquakes of magnitude beyond 5, just to mention some: one with epicentre in Scanno in 1904 of magnitude 5.8, one with epicentre exactly in Castel di Sangro in 1936 of magnitude 5.1. The most recent one is the 1984 Villetta Barrea quake with 5.1 magnitude.

Functional Description of the Hospital and Logical Scheme of the Surgery Function

The hospital has many specialties and functions. In this work attention is focused on the functionality of the Surgery, therefore only functions related to it are discussed, which essentially involve building A, C and D.

The logical scheme of the surgery function is represented in Fig. 2. It was constructed based on the following considerations. The core of the surgery function are the operating theaters (OT's), therefore the system is defined as starting from an entry point and, through a series of cooperating services, ending in either one OT. There are three OT's: one at the second floor of building A and two at the third floor of building D. In order to function, two essential services need to operate: the external electric power supply (point 2 in Fig. 1, and box a in Fig. 2) which is distributed by the switch board (point 3 in Fig. 1, and box d in Fig. 2). Before operations, the X-rays are necessary, which are located in building D (point 11 in Fig. 2, and box c in Fig. 2). Access to OT's is assured by the litter-lifts located either in building A or in building D. There is only one analysis lab located at the ground floor in building C, while the pharmacy is located at the ground floor in building E. Proper functioning of each of the above-mentioned services depends on a certain number of sub-services, therefore each service (component) is composed of sub-services (sub-components): for ex., service k (Fig. 2, inside frame) representing OT 2 is subdivided into three sub-services whose failure implies interruption of functionality of the surgery system: a) the structures of building D (structural failure), b) the partitions of the OT (cracking), c) the OT equipment (collapse for tilting and overturning). Note, for ex., that the three OT's are in parallel, therefore it is sufficient that at least one of them works to maintain the surgery service functionality. On the other hand, if either the switch board or the pharmacy fails, then the system fails.

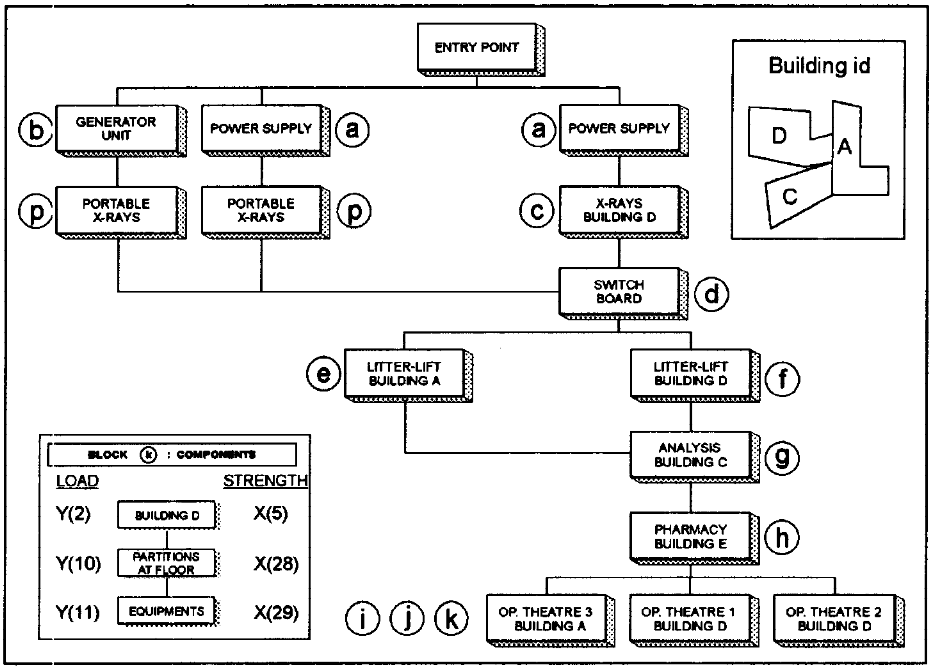

Fig. 2. Castel di Sangro hospital: Logical scheme of the surgery function.

(Sub-)Components Description

In the analysis each sub-component is identified with the random variable pertaining to its strength and with the load random variable acting on it. Coefficients of variations (c.o.v.) have been assigned, based on personal judgment. The collapse criterion was chosen so that each element fails if its strength R becomes smaller than the load S: i.e., $R-S\leq 0$.

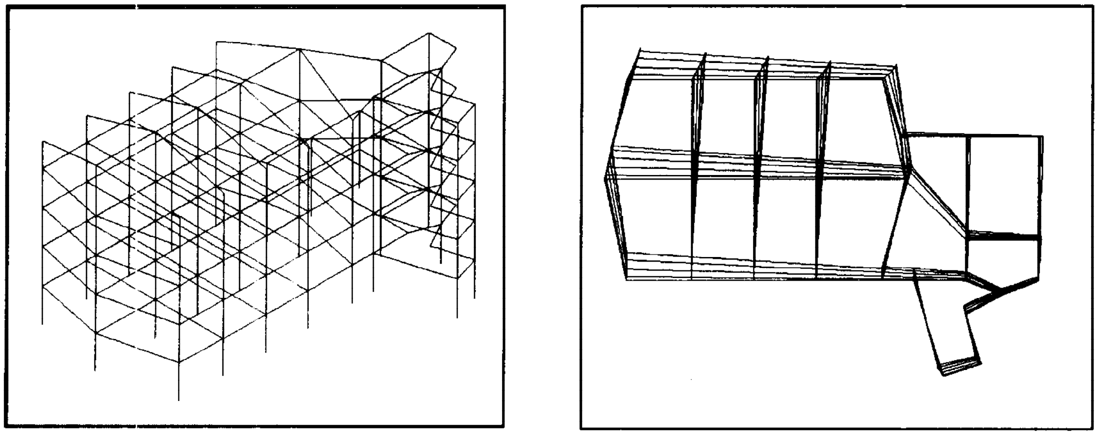

Fig. 3. One of the 3-D models used for structural analysis: building D (left).
First modal shape (in plan) of building D (right).

The mean value of the actions was evaluated through dynamic analysis of the building, with 3D elastic models (Fig. 3). The seismic action is represented by the Eurocode 8 elastic response spectrum for medium soil, scaled to the peak ground acceleration. It was assumed that the linear response in terms of displacement is representative until structural collapse occurs, considering this assumption reasonable due to the low ductility levels required in these structures. The actions on the partitions are evaluated on the basis of the interstorey drifts. The actions on the equipment are represented by the floor acceleration peak, obtained with the analysis (no floor spectra were evaluated). Building D, where two OT's are located, has the lift group extremely eccentric with respect to the center of mass of the building, therefore the response is strongly dependent on this fact (Fig. 3). The frames undergoing the highest loads are the farthest with respect to the lift group.

The strength of the structural elements, beams and columns, has been evaluated based on the original construction drawings. The flexural strengths have been evaluated assuming the characteristics of steels available at that time: yield strength 280 MPa and ultimate strength 380 MPa. Concrete has been considered to have compressive strength of 20 MPa, with an ultimate strain of 0.6%. The shear strength of the elements have been calculated, verifying the possibility of brittle shear failure for beams and columns. Finally, the relative strengths of the collapse mechanisms at each floor have been found, and the corresponding collapse accelerations determined. As expected, the beams at the higher levels resulted with low transverse reinforcement, due to the use at that time to resist shear by bending upwards the longitudinal reinforcement, therefore there is a remarkable shear failure probability where these terminate. The low-height beams are of small width, therefore a complete resisting contribution and a relatively ductile behavior has been considered. Also the columns present low transverse reinforcement, with open stirrups. Though the normal load significantly contribute to the column shear strength (Priestley et al. 1992, Aschheim and Moehle 1992), from the study of the original designs it resulted that the probability of occurrence of a premature shear failure is sensibly high, therefore the structural resistance depends also on this event. Possible soft floor mechanisms have been analyzed, based on the index proposed by Priestley et al. (1992).

The lift group in building D is rather weak. In fact, it receives a large part of the horizontal forces, and yields for ground accelerations equal to 0.05-0.07 g. It was observed that, also if the stiffness of the first two levels is reduced to account for localized yielding, the global response of the building is essentially unaltered. Shear failure of the nucleus, which presents a remarkable deformation capacity due to the low applied vertical loads, is to be excluded. It was therefore assumed that failure of the building occurs when the frames opposite to the lift group collapse. As a consequence of the low quality of the detailing, the ductility was assumed as 2.5 (mean value) and 2.0 mean value minus one standard deviation, with a coefficient of variation of 0.25.

Since it is mandatory that the OT's be aseptic, the partitions surrounding them must remain intact so that they do not produce dust. Thus, the mean limit interstorey drift was assumed as $0.002h$, where h is the interstorey height, evaluated with an infilled frame model. Partitions at the lower floors, on the other hand, can also present cracks, even though modest, without compromising the structure agibility. Thus, the mean limit interstorey drift was assumed as $0.003h$. For both cases the coefficient of variation is 0.30. The most important and delicate equipment of the OT, such as the operating table and the operating table lamp and the other equipment fixed on the ceiling, are usually structurally well fixed. The remaining equipment is neither critical nor particularly fragile, and their damage can be solved with their substitution, provided a sufficient storage is available. With the awareness of a necessary deeper look at the problem, in this application the mean value of the equipment strength was assumed as 0.50g, with respect to the floor action, with a c.o.v. of 0.30. Analogous considerations have been made for the X-rays equipment.

The lift engine and the related mechanical parts have been considered to resist up to accelerations of 0.60g (on top of the nucleus), assumed as mean value with c.o.v. equal to 0.50. For as regards the lift doors, the most critical are those located at the first and the second floor, where the nucleus yields and higher deformations are expected. It was deemed that the lift doors are blocked when an interstorey drift of $0.006h$ (corresponding to 2 cm), assumed as mean value, is attained, evaluating the acceleration that gives this deformation with the nucleus stiffness reduced of 50%. Buildings C and A were analyzed with the same criteria.

Table 1 shows the list of the random variables strengths and loads. Some strengths and loads were given relative correlation coefficients. Note that solution of the problem requires that the correlation matrix be positively defined, therefore correlations among the various components cannot be assigned freely.

X	Mean,CoV	Strength of	X	Mean,CoV	Strength of	Y	Mean,CoV	Load on
1	0.60g,20%	Ext. Power Supply	16	0.60g,50%	Lifts Doors D	A	Given,0	Intensity (PGA)
2	0.16g,50%	Gener. Unit Build.	17	0.60g,50%	Lifts Engine D	2	1.09A,50%	Building D
3	0.32g,50%	Gener. Unit Engine	18	0.60g,50%	Lifts Cages D	3	3.81A,60%	Part. Floor X-Rays
4	0.50g,50%	Gener. Unit Tank	19	0.54g,50%	Building C	4	3.00A,60%	X-Rays Equipment
5	0.54g,40%	Building D	20	3.06g,60%	Partitions Build. C	5	1.09A,80%	Building A
6	3.06g,60%	Partitions Build. D	21	0.15g,50%	Analysis Equipment	6	1.48A,60%	Lifts Building A
7	0.50g,70%	X-Rays Equipment	22	0.50g,50%	Building E	7	1.48A,60%	Lifts Building D
8	0.16g,50%	Switch Board Buil.	23	0.15g,50%	Medicine Cabinets	8	2.44A,80%	Floor on Building A
9	0.20g,50%	Switch Board	24	0.86g,60%	Partitions Area OT3	9	1.70A,40%	Equipment Build. A
10	0.36g,50%	Building A	25	0.50g,70%	Equipment OT3	10	1.36A,60%	Floor on Building D
11	0.40g,40%	Lifts r.c. walls A	26	0.98g,60%	Partitions Area OT1	11	2.50A,40%	Equipment Build. D
12	0.50g,50%	Lifts Doors A	27	0.50g,70%	Equipment OT1			
13	0.50g,50%	Lifts Engine A	28	0.98g,60%	Partitions Area OT2			
14	0.50g,50%	Lifts Cages A	29	0.50g,70%	Equipment OT2			
15	0.60g,40%	Lifts r.c. walls D						

Table 1. R.V.'s: strengths (X, lognormal) and loads (Y, normal) with adopted values for Mean and C.o.V.

Minimal Cut-set Representation of the System

Based on the logical scheme, the minimal cut-set representation of the system can be obtained. The list of cut-sets is given in Table 2, where the component numbers are the strength id's in Table 1.

C-S	Comp.	C-S	Comp.	C-S	Comp.	C-S	Comp.	C-S	Comp.	C-S	Comp.	C-S	Comp.
1	1-2	8	6-3	15	10-5	22	11-16	29	13-5	36	14-17	43	10-27-29
2	1-3	9	6-4	16	10-15	23	11-17	30	13-15	37	19	44	24-5
3	1-4	10	7-2	17	10-16	24	11-18	31	13-16	38	20	45	24-26-28
4	5-2	11	7-3	18	10-17	25	12-5	32	13-18	39	21	46	24-27-29
5	5-3	12	7-4	19	10-18	26	12-15	33	14-5	40	22	47	25-5
6	5-4	13	8	20	11-5	27	12-17	34	14-15	41	23	48	25-26-28
7	6-2	14	9	21	11-15	28	12-18	35	14-16	42	10-26-28	49	25-27-29

Table 2. Cut-Set logic: component number (strength ID) for each C-S

Iterative analysis of the system with upgrades

The evaluation of the component failure probability is carried out by means of well-known methods such as FORM (First Order Reliability Method) and SORM (Second Order Reliability Method). Since the number of components was limited through an accurate analysis of the various functions, the evaluation of the failure probability of the series-parallel system can be performed with the Ditlevsen bounds (Ditlevsen 1979). In the case at hand, the simplicity of the limit state functions of the components and their probabilistic description lead to results that coincide both with FORM and SORM method. For the solution the program Strurel (RCP Consult 1992) was used. Results are presented in the following section.

RESULTS OF THE ANALYSIS

The system failure probability P_f has been calculated for increasing values of the peak ground acceleration A_{max} and the results are illustrated in Figs. 4-5. In Fig. 4 it can be observed that already for values of A_{max} around 0.07g the hospital has a P_f=0.24, which becomes higher than 0.50 for A_{max}=0,10g. The critical cut-sets are 39, 41, 38 e 14, conditioned by the components 21 (analysis equipment), 23 (medical cabinets), 20 (partitions in building C, first floor) and 9 (switch board) (see Fig. 2). If one excludes the partitions of building C, the other two are nonstructural elements that can be easily upgraded by anchoring them and, for the first two, by anchoring the contents. It was then decided to upgrade the three elements 21, 23 and 9 with simple intervention of anchoring, to bring them up to the levels listed in Tab. 3. The intervention is surely beneficial, because it reduces P_f to 0.18, due only to the partitions of building C (cut-set 38). This confirms that substantial advantages can be obtained by means of an accurate overview of the equipments and through simple and cheap interventions.

component	before 1st upgrade		after 1st upgrade	
	mean value	c.o.v	mean value	c.o.v.
21	0.15g	0.50	0.60g	0.30
23	0.15g	0.50	0.60g	0.30
9	0.20g	0.50	0.60g	0.30

Table 3. Components strength before and after the first upgrade.

For A_{max}=0.15g a failure probability P_f between 0.63 and 0.77 is obtained, due essentially to the partitions of building C (cut-set 38, with failure probability 0.54, Fig. 4) with minor contributions particularly in the structures of building C (cut-set 37, with failure probability 0.10) and even less from cut-sets 42 and 48, with failure probability 0.07 and 0.057, linked to the failure of partitions of OT1. If one accepts a certain damage in the partitions of building C, with an interstorey drift equal to 0.006*h*, the contribution of these is obviously negligible. However, the P_f remains on high values (P_f=0.30-0.43), due to the considerable number of cut-sets with low failure probability. It is therefore concluded that a deeper intervention is needed to resist this intensity. Knowing the low quality of building C, one can for ex. foresee to move the analysis lab in building D and operate on building C so that its non-collapse is assured up to a higher threshold. Once verified that no shear failure is expected in the columns of building C, one can for ex. increase their ductility by a factor 1.5 with a cerchiatura of the base sections. Another intervention can be performed on the partitions of OT1 and OT2, increasing the mean strength from 0.002*h* to 0.003*h*. With these upgrades, the global P_f results comprised between 0.17 and 0.22 (Fig. 5). The contributing components, all with negligible probabilities around 3%, are the 8, depending on the partitions in the X-rays area in building D and on the generator unit, the 43, depending on the equipments of the OT's in building D and on the structures of building A, and finally the 11, which depends on the X-rays equipment and on the generator unit. Finally, for A_{max}=0.20g one obtains P_f=0.56-1, with critical cut-sets: 8 (with failure probability 0.27), 43 (with 0.20), 49 (equipments of the three OT's, with 0.19), and 11 (with 0.13). It should be noted that the damage is essentially nonstructural and that only the uncertainty on the effective strength of building A gives a remarkable contribution. System P_f as function of the PGA before and after the upgrade interventions are illustrated in Fig. 8.

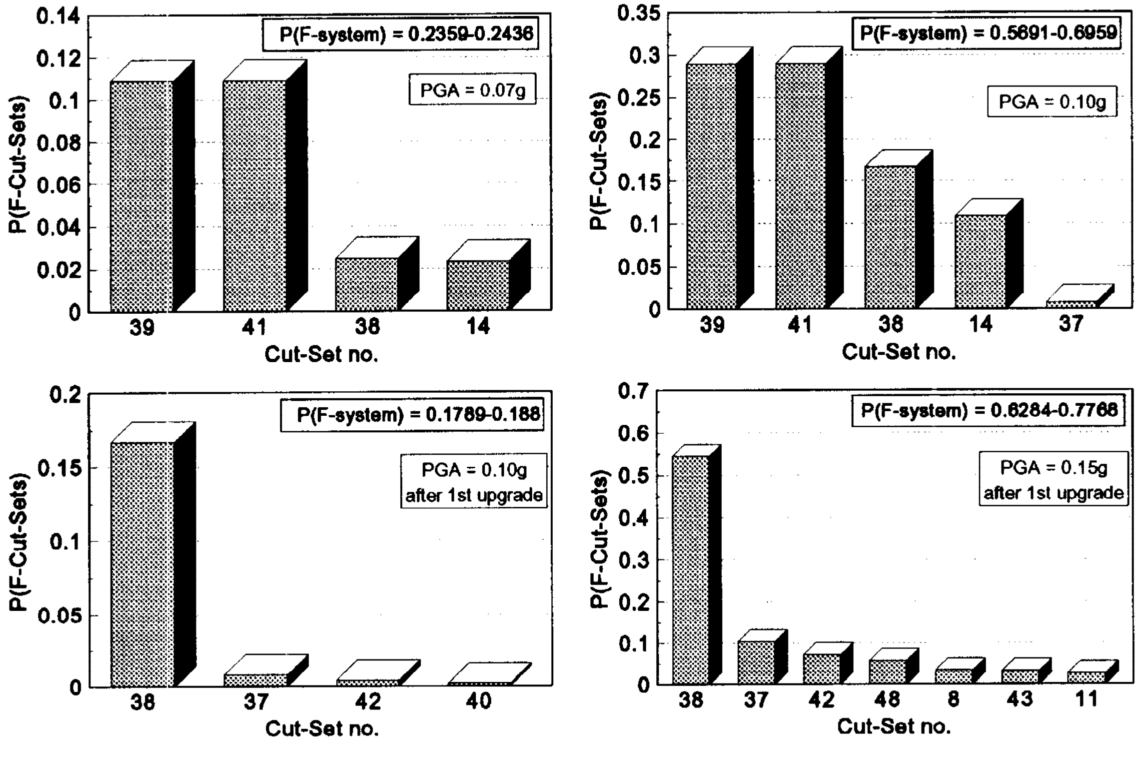

Fig. 4. Failure probability of cut-sets for PGA=0.07, 0.10g and for 0.10, 0.15g after the 1st upgrade.

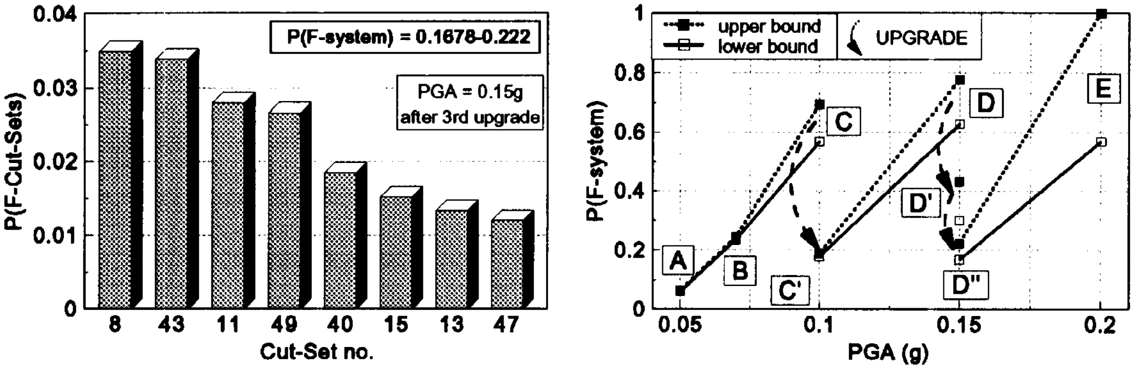

Fig. 5 Left: Failure probability of cut-sets after the 3rd upgrade.
Right: Failure probability of the system as a function of the PGA and of the upgrades.

CONCLUSIONS

A reliability-based procedure to evaluate the functional vulnerability of the surgery function of an existing hospital has been presented. The efficiency of different intervention strategies, on structural, nonstructural and equipment components has been quantified, based on the evaluations of component strengths, through available construction drawings, and of seismic loads. Functional collapse probability estimates are also obtained. By constructing the logical scheme of the surgery function, it is possible to evaluate its functional failure probability. The critical components, both structural and nonstructural, have been individuated and the advantages related to possible upgrades have been proposed.

Three intervention thresholds have been evidenced: the first one to resist intensities of 0.10g, which foresees only anchorage of the equipment; the second one to resist 0.15g, which foresees both to move the analysis lab from building C to D and the structural retrofitting of building C, in which, however, the partitions are accepted to get sensibly damaged, and finally the third, to resist 0.20g, it is necessary to foresee a series of spread interventions, essentially on partitions and equipment. Above this intensity, a structural upgrade is absolutely necessary, which in the present study was not dealt with. As for the structural elements, it seems important to stress their weakness with respect to shear, with high danger of brittle collapse. This fact is mainly to impute to the low quantity of transverse reinforcement which was adopted up to few decades ago. Partitions are a determinant element for functionality but upgrading criteria are certainly not easy to conceive.

Piping and equipments are to be studied with great attention, both for as regards the functional logic and for the details that can assure the necessary strength to horizontal actions. They are essential components for reliability and today their upgrading is possible with available techniques. In particular, the importance of an accurate study of the equipment anchorages was underlined.

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