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Abstract

The analysis of the components of an hospital system has been presented in this document. The functioning of the system under emergency condition has been examined, setting the earthquake performance requirements as function of the medical services. An index adequate to measure the performance of the system, the HTC, has been proposed. The necessary information and data, both qualitative and quantitative, for the evaluation of the component-vulnerabilities have been reported; in particular, a probabilistic-based methodology for the evaluation of the vulnerability curves of the physical components has been illustrated in detail. Fragility models for structural and non-structural elements typically presents in hospitals are presented.

This work has been carried out with the purpose of producing a state-of-the-art of available models and indicating those that are most suited for use in the European context. The selection has been based both on the data supporting the models, when possible, and on the envisaged approach within the SYNER-G general methodology for systemic vulnerability assessment.

The report also identifies research needs to improve on the currently available fragility models.

Keywords: hospital, system, structural, non-structural, equipment, vulnerability, risk, uncertainty, probabilistic, fault-tree.
Acknowledgments

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1 Seismic performance of Hospital Systems

1.1 SYSTEM COMPONENTS

Hospitals facilities belong to the category of the so-called “complex-social” systems: complex because, from an engineering point of view, these systems made of many components of different nature that jointly contribute to provide an output, the medical services; social, because hospitals provide a fundamental assistance to citizens in every-day life and their function becomes of paramount importance in the case of a disaster.

Though each complex-social system has its own peculiarities, they share common elements in the procedure through which their performance can be assessed. Complex systems can be described by the taxonomy proposed in Bea (2003), which identifies the following major components: procedures, organisation, operators, physical (structures & hardware) and environment. This system taxonomy applies very well to hospitals as illustrated in figure below.

![System taxonomy of an hospital](image)

Fig. 1 System taxonomy of an hospital

At the core of the system there are the medical services, which consist of standardized procedures established to guarantee an adequate treatment of patients. The medical services are delivered to patients by a joint contribution of the three “active” components of the system:

The facility (physical component) where the medical services are delivered. The physical component of an hospital system consists of structural elements and non-structural elements (architectural elements, basic contents and equipment). While the former are critical to preserve the life-safety of the building occupants, the latter are fundamental to preserve the hospital functionality.

The operators, which are the doctors, nurses and in general whoever plays an active role in providing medical care;

The organisation, which is responsible of setting up the adequate conditions so that the medical services can be delivered. In general, this is up to the hospital management through the development, the implementation and the supervision of the standardized procedures.
The environment includes all external influences to the functioning of a hospital system, which encompasses such diverse factors as cultural background and soil properties. It acts on all the “active” components both directly, through characteristics such as accessibility, soil conditions, etc., and indirectly, through social context, economic pressures, standards, educational system, etc..

This description should by itself be sufficient to recognise the complexities associated with the performance assessment of a hospital system, which is indeed a task significantly more demanding with respect to the assessment of “simple” systems such as residential buildings or bridges. In fact, for a correct evaluation of the system performance, contributions of all components, and their interactions, have to be appropriately accounted for.

A detailed description of each component is provided in the companion deliverables of the Syner-G project: D.2.8 – Definition of system components and the formulation of system function to evaluate the performance of critical facilities.

The index developed to measure the performance of an hospital system after the occurrence of a seismic event is presented in the remaining part of this Chapter. In Chapter 2 a methodology for the numerical evaluation of the vulnerability of the physical component is described in detail, along with the fragilities for all the relevant elements. Elements for the evaluation of the Organizational, the Human and the Environmental Components are provided in Chapters 3, 4 and 5, respectively. A summary of the risk analysis procedure is given in Chapter 6. The general taxonomy of an hospital system is reported in Appendix A.
1.2 PERFORMANCE OF HOSPITALS UNDER EMERGENCY CONDITIONS: THE HOSPITAL TREATMENT CAPACITY

The seismic performance of an hospital system is evaluated in term of the capability to accommodate a sudden incoming flow of patients requiring hospitalisation. The corresponding performance measure is the Hospital Treatment Capacity (HTC) index, defined as the number of patients with serious injuries that the hospital can treat in one hour. The evaluation of the HTC index is affected by large uncertainties since it is function of several factors of difficult quantification, ranging from the medical conditions of the patients to the amount of resources available.

The functional analysis of an hospital system under emergency condition, illustrated in the companion deliverables D.2.8 in detail, has yield the following major conclusions:

1. The hospital treatment capacity (HTC) can be quantitatively measured by the number of functioning operating theatres, which represent the bottleneck of the health-care system after a mass-casualty event that produces trauma victims;
2. The influence of the organizational and human components on the HTC can be estimated only empirically on the basis of experts judgement.
3. The relationship between the damage state of the physical component and the HTC is (analytically) evaluated by means of engineering-based methods;
4. The expression for the HTC index is the following:

\[
HTC = \alpha \cdot \beta \cdot \frac{\gamma_1 \cdot \gamma_2}{t_m}, \tag{1.1}
\]

where:
- \(\alpha\) accounts for the efficiency of the emergency plan (organizational component);
- \(\beta\) accounts for the quality, training and preparation of the operators (human component);
- \(\gamma_1\) is the number of operating theatres which remain operative after the hazardous event;
- \(\gamma_2\) is a Boolean function equal to 1 if the system “survives” and to 0 otherwise;
- \(t_m\) is the mean duration of a surgical operation (measured in hours).

The survival condition for the hospital system is defined in terms of medical services available after the seismic event (Lupoi at al. 2009). A distinction is made between essential and basic medical services. The first ones are those necessary to provide adequate care in emergency condition, both to the earthquake seriously/critically injured victims and to the in-patients of the hospital. The second ones are all the others.

Typical “essential medical services” are:
- Emergency department;
- Operating theatres;
• Intensive care unit;
• Diagnostics;
• Blood bank;
• Haemodialysis;
• Urology;
• Neonatology;
• Gynaecology/Obstetrics;
• Paediatrics;
• Laboratory;
• Pharmacy.

The essential medical services have to stay operational after the event.

The performance requirements for the system are conventionally set as follows:

a) the essential medical services have to remain operative;

b) the safeguard of human life has to be guaranteed for the basic medical services.

If the above requirements are both met, the “survival condition” is satisfied and \( \gamma_2 = 1 \); otherwise, \( \gamma_2 = 0 \).

Condition a) depends on the response of both structural and non-structural elements of the building portion where essential medical services are housed; condition b) depends on the response of structural elements only.

The fault tree technique is employed to establish the relationship between the state of the elements and the state of the system.

If the system survives (\( \gamma_2 = 1 \)), the hospital resources are measured in terms of the functioning operating theatres, \( \gamma_1 \). The derivation of the vulnerability curve for \( \gamma_1 \) is a complicated task: the large number of elements typically involved in the problem, the difficulties in evaluating the capacities of non-structural elements, the identification of failure modes are just few examples of the inherent difficulties.

Two alternative approaches are available for deriving vulnerability curves: a) structure-specific, i.e. evaluating a curve for a particular structure; b) category-based, i.e. creating a curve with the objective to be representative for a broad category of structures (e.g. buildings of a particular height range and construction material). The techniques for deriving system-specific fragilities are generally based on detailed structural analysis, while the others are based on the statistical analysis of empirical data.

The categorization of hospital systems is practically impossible since the layout of the medical services is totally facility-dependent, making each hospital a “prototype”. The structure-specific approach has to be followed. In addition, the employment of a probabilistic approach is an almost inevitable choice due to the large uncertainties characterising most of the quantities that contribute to the system response.

Advances in structural reliability analysis supported by finite element platforms have made possible to systematise the analytical approach for establishing relations between earthquake characteristics and structural response/damage (Pinto P.E. et al., 2004). These methods allow a comprehensive description of the sources of uncertainty and the development and updating of vulnerability curves incorporating both empirical evidence based on observational data and analytical predictions. A methodology for the evaluation of
the HTC and of the fragilities of its components and elements is described in the remaining part of this document.

1.3 THE HOSPITAL TREATMENT DEMAND

The treatment demand consists of the number of in-coming patients. This largely depends on the area exposed to the earthquake, e.g.: type of constructions, population density, population age, time of the day, number of medical facilities, infrastructural response, etc..

A general expression for the Hospital Treatment Demand, HTD, should be of the following form:

\[ HTD = f(\delta) \]  \hfill (3)

where \( \delta \) accounts for the environment component.

An explicit expression for the HTC index has been derived on the basis of epidemiologic studies and of casualty models, as reported in detail in section 5.3.

Epidemiology is the study of patterns of disease and injury in human populations. The causes of major earthquake-related injuries have been identified and two indexes have been derived to measure the medical severity of an earthquake event as a function of the patients’ conditions.

The number of in-coming patients are estimated by the so-called “casualty models”. The one model proposed by Coburn and Spence (1992) and simplified by Nuti and Vanzi (1998) is adopted for the European context.
2 The Physical Component

2.1 ELEMENTS OF THE COMPONENT

The physical component includes a large variety of elements different in nature and scope such as structures, installations, furniture and equipment, medicines, etc.

The structural elements are sub-systems, elements, or components that are part of the load-bearing system: beams, slabs, columns, joints, walls, etc. The non-structural elements are sub-systems, elements, or components that are not part of the load-bearing system, but nevertheless are part of the building dynamic environment caused by the earthquake. Typical classification subdivides the non-structural elements into three categories: architectural elements, basic installations and equipment/contents.

<table>
<thead>
<tr>
<th>Architectural</th>
<th>Basic installations</th>
<th>Building content (Equipment / furnishing)</th>
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<tbody>
<tr>
<td>Stairs</td>
<td>Power system</td>
<td>Mechanical and electrical equipment</td>
</tr>
<tr>
<td>Exterior and partition walls</td>
<td>Water system</td>
<td>Shelves and rack systems</td>
</tr>
<tr>
<td>Doors</td>
<td>HVAC system</td>
<td>Kitchen appliances</td>
</tr>
<tr>
<td>Parapets and cornices</td>
<td>Medical gases</td>
<td>Vending machines</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Fire protection</td>
<td></td>
</tr>
<tr>
<td>Windows</td>
<td>Communication system (internal and external)</td>
<td>Medical and laboratory equipment</td>
</tr>
<tr>
<td>Cladding</td>
<td>Conveying system</td>
<td>Medicine containers</td>
</tr>
<tr>
<td>...</td>
<td>Ductwork and piping systems</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>Lighting system</td>
<td>...</td>
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While the response of structural elements under the earthquake action has been the object of extensive studies for the past three decades, and well-established capacity models are available nowadays, for the non-structural ones the current situation is quite the opposite. In fact, few capacity models are available for a limited number of non-structural elements and these are all characterised by large uncertainties. An overview on this topic can be found in (Shinozuka, 2001), (Lupoi et al., 2008), (Grigoriu et al., 1988).

2.2 PROBABILISTIC METHODOLOGY

The general methodology for the evaluation of the "probability of failure" of hospital systems proposed by (Lupoi et al., 2008) is illustrated in this section.

The performance of the system is expressed in terms of the mean annual frequency of exceedance $\lambda$ of given levels of quantifiable (performance) measures, also called decision variables:

$$\lambda(\mathbf{dv}) = \int P(\mathbf{DV} > \mathbf{dv} | \mathbf{IM}) \cdot d\lambda(\mathbf{IM}).$$  (2.1)
where $\mathbf{DV}$ is the vector collecting the decision variables, $\mathbf{IM}$ is the intensity measure of the earthquake, $P(\mathbf{DV} > \mathbf{dv} | \mathbf{IM})$ is the vulnerability curve, $\lambda(\mathbf{IM})$ is the hazard curve.

The decision variables are expressed as function of random quantities describing the state of the system, the so-called damage measures. These latter, in turn, are function of the basic random variables of the problem, which can be classified in the following categories:

- The system properties, collected in the $\mathbf{x}$ vector;
- The model errors, both in the element capacity models, $\varepsilon_c$, and in the relationship between damage measure and decision variables, $\varepsilon_{\mathbf{DV}}$;
- The external hazard, both in the intensity $\mathbf{IM}$ of the seismic event and in the record-to-record variability of the structural response $\varepsilon_{eq}$.

The final expression for the decision variables is of the following form:

$$
\mathbf{DV} = \mathbf{DV}[\mathbf{DM}(\mathbf{IM}, \mathbf{x}, \varepsilon_{eq}, \varepsilon_c)\mathbf{x}, \varepsilon_{\mathbf{DV}}] 
$$

where $\mathbf{DM}$ is the vector of the random damage measures.

The introduction of the “intermediate” random vector $\mathbf{DM}$ allows splitting the assessment problem in two parts:

- deriving the complementary cumulative distribution function (CCDF) for the damage measures conditional to the earthquake intensity: $P(\mathbf{DM} > \mathbf{dm} | \mathbf{IM})$;
- compute the conditional CCDF for the decision variables, $P(\mathbf{DV} > \mathbf{dv} | \mathbf{IM})$, through the $\mathbf{DV}$-$\mathbf{DM}$ relationships (eq.2.2).

The risk of the system (i.e. the mean annual frequency of failure) is obtained from the convolution of $P(\mathbf{DV} > \mathbf{dv} | \mathbf{IM})$ with the hazard function, $\lambda(\mathbf{IM})$:

$$
\lambda(\mathbf{dv}) = \int P(\mathbf{DV} > \mathbf{dv} | \mathbf{DM}, \mathbf{IM}) \cdot dP(\mathbf{DM} > \mathbf{dm} | \mathbf{IM})d\lambda(\mathbf{IM}) 
$$

In practice, the probabilistic risk analysis (PRA) is carried out by the sequence of steps schematically represented in Fig. 2.

![Fig. 2 Steps in the performance assessment procedure (Lupoi at al. 2008)](image)

1. **Hazard analysis:** it consists in the evaluation of the annual probability of exceedance of the earthquake intensity for the site of the facility. The probabilistic seismic hazard analysis (PSHA) methodology (Cornell, 1968), or one of its derivatives available in literature (e.g.
(Backer et. al, 2005)), can be employed for this task; the reader can refer to deliverable D.2.13 for a comprehensive report on this subject.

2. **Damage analysis**, which is subdivided in the following two major tasks.

2.1 **Response Evaluation**: an approximate functional relationship, \( D(x, \varepsilon_{eq}, IM) \), between the elements demands, \( D \), and the basic r.v.’s is established through numerical analyses.

The method proposed in Lupoi et al. (2005) is employed. For a given reference intensity measure \( IM_{ref} \), the dependence of the demands on the basic random variables related to the input, \( \varepsilon_{eq} \), is evaluated for the mean value \( \mu_x \) (of the basic random variables related to the structural system \( x \)) by repeating the analyses for an adequate number of recorded ground motions scaled to \( IM_{ref} \). The dependence of the demands on the random system properties \( x \) is neglected for the sake of simplicity, i.e. \( D = D(\varepsilon_{eq}, IM) \). This approximation is customary in earthquake engineering since it is commonly accepted that, in the majority of applications, the variability of the ground motion is much more influential on the structural response than that introduced by the structural properties \( x \).

In practice, for a given level of \( IM_{ref} \), a non-linear time-history analysis is carried out for each of the \( N \) recorded ground motions selected to represent the seismic hazard, assigning the mean value to the random structural properties (i.e. \( x = \mu_x \)). For each analysis, the maximum value of the demands over time is recorded:

\[
D_{ik}(\mu_x, IM_{ref}) = \max_i D_{ik}(\mu_x, IM_{ref})
\]  

where the sub-index \( i \)-th refers to the demand and the sub-index \( k \)-th to the analysis. For the selection of ground motions, the reader can refer to (Lupoi et al. 2008), (Iervolino et al., 2005), Deliverable D.2.13.

2.2 **Damage state determination**: demands and corresponding capacities are compared through a Monte Carlo simulation approach. The complementary distribution of the damage measures conditional to the earthquake intensity, \( P(DM > d | IM) \), is derived.

The state of each element is obtained comparing capacity and demand, i.e. using the so-called limit state function which, for the \( i \)-th element, can be put in the form:

\[
g_{i,j} = C_{i,j} - D_i
\]  

where \( C_{i,j} \) is the capacity for the \( j \)-th limit state, usually established from semi-empirical models with a mechanical base of variable weight.

Making explicit the dependence of capacities and demands from the random variables, eq.(2.5) can be re-written as:

\[
g_{i,j}(x, \varepsilon_C, IM, \varepsilon_{eq}) = C_{i,j} - D_i(x, IM, \varepsilon_{eq}),
\]
It is noted that the dependence of the capacity from the demand is explicitly acknowledged in eq.(2.6), which accounts for all possible sources of uncertainty. In practice, it is applicable only if a complete knowledge of the element (in terms of properties, failure modes, capacity models) is achievable, as it may be the case for structural elements. Eq.(2.6) may actually be not applicable for non-structural elements due to the lack of such a detailed knowledge. In this case it has to be simplified into:

$$g_{i,j} = C_{i,j}(x_1, \varepsilon_c) - D_j(x_2, IM, \varepsilon_q), \quad (2.7)$$

where (a) the capacity does not depend on structural response, and (b) the capacity and the demand models do not have random variables in common.

The damage state of the whole system is estimated by a Monte Carlo simulation, which consists of:

- sampling from the basic random variables: $x$, $\varepsilon_c$;
- evaluating the elements capacities from the corresponding models;
- sampling randomly from the $N$ demand vectors obtained from dynamic analysis;
- estimating the elements damage measures $DM$ by comparing capacities $C$ and demands $D$ by means of eq.(2.6) or eq.(2.7).

Monte Carlo simulation with a sufficient number of samples yields the conditional exceedance probability $P(DM > dm|IM_{ref})$. The complete vulnerability curve is obtained by repeating this step for a convenient number of $IM_{ref}$.

3. Performance analysis: the complementary distribution for the decision variables conditional to the earthquake intensity, $P(DV > dv|IM_{ref})$, is derived from that of the damage measures by means of the relationship in eq. (2.2).

4. Risk analysis: the unconditional mean annual frequency of non-performance is evaluated by convolution of the hazard, $\lambda(IM_{ref})$, with the vulnerability $P(DV > dv|IM_{ref})$ (eq.(2.1)).

The accuracy of a PRA resides, for a good part, in a realistic and comprehensive description of all important sources of uncertainty. The uncertainties that affect the reliability of the physical components can be broadly classified as follow:

- those related to the external hazard
- those related to the evaluation of the structural response, i.e. the finite element model, the type of analysis (static or dynamic, linear or non-linear, type of non-linearity, soil-structure interaction), etc.;
- those related to the knowledge of system properties, such as size, weight, stiffness, strength, characteristics of the interface between the element and the structure;
- those related to the modelling of the capacities of both structural and non-structural vulnerable elements;
- those related to performances, such as the definition of damage levels and of the consequences associated to exceeding any limit-state;
2.3 CAPACITY MODELS FOR ASSESSMENT

Capacity and demand have to be expressed in terms of local response quantities well-correlated to damage to adequately represent the actual state of an element. The definition of models capable of describing elements capacity is a major task in the overall assessment procedure. In fact, “capacity models developed and used for assessment purposes bear a conceptual difference with respect to those used in design. The latter generally tend to be simple of use and approximated in a conservative way, which makes them unsuitable for a consistent evaluation of risk. Risk assessment requires explicit consideration of all relevant uncertainties, aleatoric and epistemic, and probabilistic models that are unbiased. A conservative model does not comply with this requirement.” (LESSLOSS, 2005).

The definition of a capacity model is generally based on one of the following approaches: empirical, theoretical or judgment-based.

*Empirical* approaches are based on the statistical analysis of the performance of the element during past earthquakes. These data may derive from instrumented and non-instrumented buildings. Instrumented buildings are a potentially excellent source of information not yet adequately exploited. Non-instrumented buildings represent a less reliable, but more readily available source of information: a damage-motion relation can be obtained relating data on damage from detailed damage inspections with data on motion from structural analysis. Empirical approaches include also experimental tests, one of the most reliable sources of data to study the damage as a result of applied loads, since everything in an experiment is monitored closely. Unfortunately the results and the procedures applied in the tests are not always well-documented.

*Theoretical* approaches are based on analytical simulations (static and dynamic analysis) of a mechanical model of the element.

*Judgment-based* approaches represent the opinion of experts.

Preference for a given approach depends on circumstances. In practice, the information for the development of capacity models has been usually obtained empirically, but it is recognized the need of combining the three approaches to achieve a good capacity model.
2.4 R.C. STRUCTURAL ELEMENTS

Failure mechanisms in RC structures may be localised at the elements level (beam, columns and joints) or at a global scale for the formation of a mechanism (more elements involved).

Local response parameters can be: force-quantities, such as shear failure (force mechanisms), to evaluate the state of the element with respect to the activation of force-controlled failure mechanisms; displacement/deformation quantities, such as inter-storey drift ratios or chord-rotations, to evaluate the element damage state with respect to displacement-related mechanisms.

The global failure of the RC structure typically occurs for the formation of a weak-storey mechanism.

The generic fault tree for RC structures is then represented in Fig. 3.

Fig. 3 Generic fault tree of structural failure for R.C. elements

A vast literature is available on capacity models for R.C. structural elements. However, the available capacity formulas are generally based on relatively weak mechanical basis, integrated with empirical knowledge. In the proposed method the capacity terms are expressed in the multiplicative format:

\[ C_i(x, \varepsilon_{Ci}) = \overline{C}_i(x) \varepsilon_{Ci} \]

where \( \overline{C}_i(x) \) is the value obtained by semi-empirical formulas available in the literature and \( \varepsilon_{Ci} \) is a model-error term accounting for scatter and, when necessary, for bias as well. The type of distribution of \( \varepsilon_{Ci} \) is based on expert judgment.

The recommended models for the estimation of members shear strength, deformation and drift capacity are described in the following sections.
2.4.1 Shear capacity

The shear-strength model for beams, columns and walls, originally presented in Kowalsky and Priestley (2000) and reported in its revised version in (fib, 2003), is often adopted for the capacity of the shear failure mode, since it allows evaluation of capacity under bi-axial loading. The model gives the shear strength as the sum of three distinct contributions, resulting in the following capacity:

\[
C_V(x) = (V_c + V_t + V_p)\cdot \varepsilon_V
\]

where \(V_c\) represents the concrete contribution, \(V_t\) the transverse steel contribution, and \(V_p\) the axial load contribution to shear resistance. These contributions are given by:

\[
V_p = \frac{b - x}{2L_x} \cdot \min(N, 0.55A_c f_c)
\]

\[
V_t = 0.16 \cdot k_t \cdot \max(0.5, 100\rho_{st}) \cdot \left(1 - 0.16 \cdot \min(5, \frac{L_x}{b}) \right) \cdot \sqrt{f_t A_t}
\]

\[
V_s = \rho_s \cdot b_s \cdot z \cdot f_s \cdot \cot \theta
\]

where \(h\) is the depth of the section, \(x\) the depth of compression zone, \(L_x = M/V\) the shear span length, \(N\) the axial load (positive for compression), \(A_c\) the area of concrete, \(f_c\) the concrete strength; \(k_t = \max(0, 1 - 0.08 \cdot \min(5, \mu_p^{pl})\) accounts for the degradation of the shear strength with the ductility demand, \(\rho_{st}\) is the total ratio of longitudinal steel, \(\mu_p^{pl} = \mu_p - 1 = \theta_p^{pl} / \theta_p\) is the ratio of the plastic component of chord rotation at failure (total chord rotation minus value at yield) to the yield chord rotation, \(\theta_p\); \(\rho_s\) denotes the ratio of transverse steel; \(z \approx d - d' \approx 0.9 \cdot d\) is the internal level arm; \(\theta\) is the inclination of the compression struts assumed equal to 45°.

The model, originally calibrated for circular columns (with a \(CoV\) of 20.1%), is extensively evaluated in (fib, 2003) where it is shown that the mean value of the ratio of experimental to predicted results equals 0.83 for rectangular sections with a \(CoV\) of 26.1%. The lognormal model correction term, \(\varepsilon_V\), included in eq.(2.6), is therefore assigned mean 0.83 and \(CoV\) equal to 0.261 when used to evaluate the random shear strength of elements with a rectangular cross-section.

The shear-strength of beam-column joints is generally expressed in terms of limits to the principal stresses, tensile and compressive. These are taken from Eurocode 8 (CEN, 2003) as:

\[
\sigma_t = 0.3 \cdot f_{ck}^{2/3}
\]

\[
\sigma_c = 0.6 \cdot \left(1 - \frac{f_{ck}}{250}\right) \cdot f_{cd}
\]

where \(f_{ck}\) and \(f_{cd}\) are the characteristic compressive and tensile strength, respectively.

As noted in LESSLOSS (2005), the eqs.(2.12) and (2.13) are not associated with an estimate of their dispersion. Based on expert judgement, a coefficient of variation of the order of 0.30-0.35 and of 0.20-0.25 for the compressive and tensile stresses, respectively, is suggested.
2.4.2 Deformation capacity

The ultimate drift capacity is often modelled after Panagiotakos and Fardis (2001) as:

\[
\beta_{\theta,\beta} = \left\{ \beta_{\theta,\beta} \cdot \alpha \cdot 0.25 \cdot \left[ \max(0.01, \omega) \right]^{0.25} \cdot \left[ \frac{L_{\alpha} b}{h} \right]^{0.4} \cdot 2.5^{0.025} \cdot 1.55^{0.001} \rho_{\text{eff}} \right\} \cdot \varepsilon_{\theta,\beta} \tag{2.14}
\]

where \( \beta_{\theta,\beta} \) accounts for the type of the steel: 0.016 for ductile hot-rolled or heat-treated steel and 0.0105 for cold-worked steel,

\[
\alpha = \left( 1 - 0.46\alpha_{\theta,\beta} \right) \left( 1 + 0.6\alpha_{\theta,\beta} \right) \left( 1 - \frac{3}{8}\alpha_{\text{wall}} \right)
\]

with \( \alpha_{\text{cy},\beta} \), \( \alpha_{\text{sl},\beta} \) and \( \alpha_{\text{wall},\beta} \) binary coefficients \((0,1)\) to indicate whether the load is monotonic or cyclic, whether reinforcement pullout is possible or not and whether the element is a wall or not, respectively;

\[
\nu = \frac{N}{b \cdot h \cdot f_{c}}
\]

is the normalised axial force, ratio between the axial load (positive for compression) and the maximum compressive axial load ; \( \omega \) and \( \omega' \) are the mechanical ratios of tension and compression longitudinal reinforcement; \( f_{c} \) is the concrete strength, \( h \) and \( b \) are the depth and the width of the section; \( CC = k_{c} \cdot \rho_{s,\beta} \cdot f_{\gamma,\beta} \cdot f_{c} \) is the effective normalised confining pressure provided by transverse reinforcement in the direction of the lateral sway; \( \rho_{s,\beta} = A_{s,\beta} / (b_{\gamma} \cdot s) \) is the volumetric ratio of the lateral reinforcement; \( \rho_{d} \) the diagonal reinforcement ratio.

For new members the median of the experimental to predicted values is shown to be equal to 1.00 with \( CoV = 0.425 \); for old non-seismically detailed members the median is 0.85 and the \( CoV \) \( 0.42 \) \( \text{fib}, 2003 \). The parameters of the error term in eq.(2.14) are set accordingly.
2.4.3 Soft-storey capacity

The weak-storey failure corresponds to a considerable reduction of the lateral stiffness of a floor due to the yielding of all the columns of that floor.

Yield drift capacity can be modelled as:

\[
C_{\alpha}(x) = \frac{\Delta}{L_s} = \frac{\phi_s L_s}{3L_s} = \frac{2.1 f_y L_s}{3E_s h} \epsilon_{\phi_s} \tag{2.15}
\]

where the yield displacement \( \Delta \) is given as function of the shear span \( L_s \) and the yield curvature \( \phi_s \), which depends on the section height \( h \) and the steel yield strain \( f_y / E_s \). The shear span is assumed to be equal to half of the member height, \( L_s = 0.5H \), possible deviations from this value being accounted for in the error term \( \epsilon_{\phi_s} \) that can be described by a lognormal random variable with unit median and \( CoV \) equal to 0.20.
2.5 NON-STRUCTURAL ELEMENTS

The selection of the local response parameter for a *non-structural* element depends on which of the earthquake effects governs its repose. A broad-type classification is provided in Fig. 4, where the following major effects are identified:

- local acceleration, which may cause the element sliding or overturning;
- structural deformation;
- relative movements between adjacent or connected structures.

In general, a *restrained* non-structural element is drift sensitive, while a *free* non-structural element is acceleration sensitive. The differential displacement sensitive elements are those which provide a continuous link across a separation joint or between two different structures.

Elements that hang from floor slabs and beams, such as many mechanical and electrical components, ceilings and contents, are examples of acceleration sensitive elements; glazing, doors and partition walls, which are tightly locked into the structure, are examples of structural deformation sensitive elements. Some components are sensitive to both inter-storey drift and peak floor acceleration. Elevators have rails, door and other components that are damaged primarily by inter-storey drift ratios, while others, such as the motor and counterweights, are damaged as a result of floor accelerations.

Items that are connected to objects with independent movement, i.e. utilities extended across the separation joints, should be capable of providing functional continuity and therefore are sensitive to differential displacements.

![Fig. 4 Effects of earthquakes on non-structural elements (from FEMA 74)](image-url)
Accordingly to the considerations above, non-structural elements are usually classified as: acceleration-sensitive, deformation (drift)-sensitive or differential displacement sensitive. The corresponding fault tree is represented in Fig. 5.

![Fig. 5 Non-structural element classification by failure mechanism](image)

The definition of capacity models for non-structural elements is not straightforward. In fact, although the general working principles are the same for all elements, each one has its own unique adaptation that makes it different from the others. For example, the interface between the elements and the structure can take different forms: elements can be fixed to the floor, supported by a layer of interposed material intended to isolate them from the floor motion, or placed securely in a rack fixed to the floor and wall, etc..

The importance of these characteristics, such as details of construction and equipment configurations, has been pointed out in Porter et al. (1993), where these are identified as the primary causes of failure in moderate and large earthquakes.

Since an accurate modelling for all non-structural elements is not practicable, the following approach is adopted:

- *generic* capacity models are employed for classes of “non-critical” elements.
- *specific* capacity models are developed for critical elements

---
2.5.1 Generic capacity model for drift-sensitive elements

The median values of the capacity of a generic drift-sensitive non-structural element are reported for different states of increasing damage in Table 2 (Hazus, @).

<table>
<thead>
<tr>
<th>State</th>
<th>Median Drift Capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight</td>
<td>0.4</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.8</td>
</tr>
<tr>
<td>Extensive</td>
<td>2.5</td>
</tr>
<tr>
<td>Complete</td>
<td>5.0</td>
</tr>
</tbody>
</table>

The operational limit state corresponds to the “slight damage” level.

The dispersion of each damage threshold can be evaluated as the sum of the following two contributions:

- dispersion due to uncertainty in the damage state threshold of non-structural elements, \( \beta_1 = 0.5 \);
- dispersion due to variability in the capacity properties of the non-structural elements, \( \beta_2 = 0.2 \).

The resulting error term is thus described by a lognormal random variable with unit median and coefficient of variation \( \beta = \beta_1 + \beta_2 = 0.7 \). The resulting fragility curves are shown in Fig. 6.

![Fig. 6 Fragility curves for drift-sensitive non-structural elements](image-url)
2.5.2 Generic capacity model for acceleration-sensitive elements

The median values of the capacity for an acceleration-sensitive non-structural element as a function of the type of seismic prescriptions enforced by the Code at the time of the design (denoted as seismic design level) are given for different states of increasing damage in Table 3 (Hazus, @).

Table 3 Peak floor acceleration capacity (in $g$) for non-structural elements

<table>
<thead>
<tr>
<th>Seismic Design Level</th>
<th>Slight</th>
<th>Moderate</th>
<th>Extensive</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Code</td>
<td>0.45</td>
<td>0.90</td>
<td>1.80</td>
<td>3.60</td>
</tr>
<tr>
<td>Moderate-Code</td>
<td>0.375</td>
<td>0.75</td>
<td>1.50</td>
<td>3.00</td>
</tr>
<tr>
<td>Low-Code</td>
<td>0.30</td>
<td>0.60</td>
<td>1.20</td>
<td>2.40</td>
</tr>
<tr>
<td>Pre-Code</td>
<td>0.30</td>
<td>0.60</td>
<td>1.20</td>
<td>2.40</td>
</tr>
</tbody>
</table>

These values have been derived for the “Special Buildings” category, characterized by increased anchorage strength of non-structural elements. For a “General Building”, where no special provisions for anchoring have been enforced, the values in Table 3 have to be divided by a factor of 1.5.

The operational limit state corresponds to the “slight damage” level.

The dispersion of each damage threshold can be evaluated as the sum of the following two contributions:

- dispersion due to uncertainty in the damage state threshold of non-structural elements, $\beta_1 = 0.6$;
- dispersion due to variability in capacity properties of the non-structural elements, $\beta_2 = 0.2$.

The resulting error term is thus described by a lognormal random variable with unit median and coefficient of variation $\beta = \beta_1 + \beta_2 = 0.8$.

The fragility curves for a Special Building designed according to an High-Code are shown in Fig. 7.

![Fig. 7 Fragility curves for acceleration-sensitive non-structural elements (High-code)](image-url)
2.6 NON-STRUCTURAL ELEMENTS: ARCHITECTURAL

The architectural elements are typically built-in non-structural components that form part of the building. Those that have jeopardised the functionality of several hospitals in past earthquakes are:

- interior and exterior walls
- ceilings
- windows, glasses and doors

Walls are made of masonry or other materials and are typically stiffer and more brittle than the structural frame; therefore, they tend to develop cracks when the building is subjected to earthquake shaking. Usually, the crack growth is initiated at (the corner of) an opening in the wall. The failure of either interior or exterior walls can be attributed to (a) excessive flexural out-of-plane stresses induced by floor accelerations or (b) excessive in-plane shear stresses induced by inter-storey drifts imposed on the building structure. Studies on the seismic performance of walls have been performed, among others, by Freeman (1977), by Rihal (1982) and by Cohen (1995).

Ceilings are non-structural elements that are sensitive to both deformation and acceleration. The deformation of the floor slabs can cause horizontal distortion and the deformation of the main structure, leading to possible loss of support and fall of the ceiling. Gates and McGavin (1998) point out the interaction between the ceiling system and both the fire sprinkler system and the lighting fixtures. References to this type of non-structural elements are, among others, Eidenger and Goettel (1998), Yao (2000), Badillo et al. (2003) and Gann et al. (2005).

Elements that are attached to the structure or to non-structural walls, such as doors, windows, glasses, can twist and buckle when they are subjected to large deformations. Most often deformation of the structural frame can jam the element (as in the case of doors) or cause failure (as in the case of glasses) due to the inadequate edge clearance around the item (door, glass, windows, etc.). The performance of glass doors, windows and glazing during earthquakes is highly dependent on the deformation capacity provided to the brittle material with respect to it supporting frame. Failure of this kind of elements causes not only a problem for the functionality but could also produce injuries. Studies on this category have been conducted, among others, by Bouwkamp and Meehan (1960), by Nakata et al (1984) and by Behr and Worrell (1998).

The generic fault tree for architectural elements is illustrated in Fig. 8.

![Generic fault tree for architectural non-structural elements](image-url)
The behaviour of architectural elements has been extensively studied and it is adequately understood nowadays. Nevertheless, well-defined limit state equations are not available due to the large variety of these elements. For this reason a global criterion has been adopted, weighting the information available in the literature with the results of the visual surveys carried out in many Italian hospitals.

The capacity parameters given in Table 4 refer to a moderate damage state of the components, which is the level beyond which functionality of the building is compromised.

**Table 4 Probabilistic characterisation of the capacity of the architectural elements**

<table>
<thead>
<tr>
<th>Object</th>
<th>Demand</th>
<th>Distr.</th>
<th>Mean</th>
<th>CoV</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls</td>
<td>Drift</td>
<td>LN</td>
<td>0.75%</td>
<td>0.23</td>
<td>Rihal (1982)</td>
</tr>
<tr>
<td>Glazing, Doors,</td>
<td>Drift</td>
<td>LN</td>
<td>4.60%</td>
<td>0.33</td>
<td>Behr and Worrell (1998)</td>
</tr>
<tr>
<td>windows, etc.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceilings</td>
<td>Acceleration</td>
<td>LN</td>
<td>0.90g</td>
<td>0.30</td>
<td>Eidenger and Goettel (1998)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Badillo et al. (2003)</td>
</tr>
</tbody>
</table>
2.7 NON-STRUCTURAL ELEMENTS: BUILDING CONTENT

Building contents include furnishings, medical and industrial equipment, general supplies, shelves, etc. Equipment and supplies are essential for the functioning of the facility and for protecting the lives of its occupants, and yet they can represent a danger in case of an earthquake.

Examples of equipment and relative anchorages are shown in Fig. 9 for an operating theatre and a radiology room. A list of essential equipment and supplies for life-support of patients and for emergency care after an earthquake is given in Table 5.

Table 5 Essential equipment and supplies

<table>
<thead>
<tr>
<th>Building content</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Essential diagnostic equipment:</td>
<td>Phonendoscopes, tensiometers, thermometers, otoscopes, ophtalmoscopes, reflex hammers and flashlights should always be available.</td>
</tr>
<tr>
<td>Mobile carts</td>
<td>Carts used to move special equipment for crisis intervention are particularly important for saving lives and storing supplies. Objects must be secured to the trolley. When not in use the trolleys must have their brakes on and be parked against dividing walls.</td>
</tr>
<tr>
<td>Respirators and suction equipment</td>
<td>This equipment should be secured in such a way that they do not be disconnected from the patients.</td>
</tr>
<tr>
<td>Hazardous substances</td>
<td>Storage shelves containing medicines or chemicals, if overturned, can constitute a hazard by virtue of their toxicity, both in liquid and in gas form. On many occasions fires start by chemical action, overturned gas cylinders or ruptures in gas supply lines.</td>
</tr>
<tr>
<td>Heavy articles</td>
<td>Heavy articles such as televisions, X-ray equipment, ceiling lamps, sub-stations can pose a threat or be damaged if they fall.</td>
</tr>
<tr>
<td>Filing cabinets</td>
<td>They store data and a large amount of information necessary for patient treatment.</td>
</tr>
<tr>
<td>Computers</td>
<td>They must be well secured to desks to prevent them from falling and losing their function. Computer services should be backed up by the emergency power plant.</td>
</tr>
<tr>
<td>Refrigerators</td>
<td>Particularly important for the blood bank, medicine and food refrigerators to maintain continuous cooling. They should be connected to the emergency power supply.</td>
</tr>
</tbody>
</table>

In the practice, however, the on-site verification of the anchorages of all the contents of a hospital is practically unfeasible, both for the excessive number of elements and for the limited possibility of investigation. As a result, it is customary to assume that all items susceptible to moving are properly anchored and, consequently, their vulnerability is not
explicitly considered in the analysis. Alternatively, a fragility curve based on engineering judgement may be derived on the basis of field investigation.

2.8 NON-STRUCTURAL ELEMENTS: BASIC INSTALLATIONS

Across all occupancies, including essential facilities, the most disruptive kind of non-structural damage is the breakage of water lines inside buildings, including fire sprinklers, domestic water, and chilled-water systems. Leaked water can travel quickly and extensively throughout a building.

Second in significance is failure of emergency power systems. The power outage is usually so extensive that reliable backup power is necessary for essential facilities to operate. Others frequently damaged installations, among those essential for the functioning of hospitals, are the conveying and the medical gas systems.

Each of such systems can be subdivided in two main components:

(a) **Generation**: it can be provided by an internal or an external source. However, in an emergency situation, all the essential systems have to be complemented with an internal source. Examples of internal sources are electrical generator, water tank, gas tank. Their typical mode of failure is the damage of anchorages.

(b) **Distribution**: it includes pipes for water, for wastewater, for fuel, for gas, and electrical conduits (lines) that run underground or above grade, inside and outside the building. Damage to above ground transmission lines typically occurs along unsupported line sections when lines crack, leak, or fail. Damage to underground transmission lines usually occurs in areas of soil failure where the line sections cannot accommodate soil movements or differential settlements. Damage can also occur when other equipment shifts or falls onto the line, or if a piece of equipment the line is connected to suffers damage. Lines that run across a seismic joint without an expansion joint may suffer damage to their connections or get torn apart. It is noted that electric power is necessary for the proper functioning of the distribution lines.

The generic fault tree for a basic installation is represented in Fig. 10.

![Fig. 10 Fault tree of a generic basic supply](image-url)
2.8.1 Medical gas

The medical gas system of an hospital typically consists of tanks and cylinders of the medical gases (oxygen, nitrogen, etc.), the distribution lines (pipes) and several other pieces of equipment necessary to the normal functioning such as, for example, electric pumps. The cylinders and the auxiliary equipment are usually located in a large room at the base floor of the building.

Examples for cylinders and the auxiliary equipment are shown in Fig. 11; for this case, a proper anchorage is noted.

Examples for not properly anchored oxygen and nitrogen cylinders are shown in Fig. 12.

A piping system and an oxygen bottle (tank) are shown in Fig. 13. It can be noted that the piping system is not provided by flexible couplings.

![Fig. 11 Examples for anchorages of different equipment of medical gases network](image1)

![Fig. 12 Example of oxygen cylinders – detail of anchorage](image2)

![Fig. 13 Examples for distribution lines (left) and for oxygen bottle tank (right)](image3)
The generic fault tree for the medical gas system is shown in Fig. 14.

![Fault tree of medical gases network](image)

The probabilistic description of the vulnerable components for a medical gas system is given in Table 6.

**Table 6 Probabilistic characterisation of the capacity of the medical gas system**

<table>
<thead>
<tr>
<th>Object</th>
<th>Demand</th>
<th>Distr.</th>
<th>Mean</th>
<th>CoV</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinders</td>
<td>Acceleration</td>
<td>LN</td>
<td>0.50g</td>
<td>0.25</td>
<td>Expert judgment</td>
</tr>
<tr>
<td>Pipes</td>
<td>Drift</td>
<td>LN</td>
<td>0.90%</td>
<td>0.25</td>
<td>Kuwata and Takada (2003)</td>
</tr>
</tbody>
</table>
2.8.2 Power System

The power system of an hospital buildings is typically composed of:

- MV-LV (Medium Voltage - Low Voltage) transformation station;
- Uninterruptible Power System (UPS);
- Emergency Power Generator (EPG);
- Transmission lines;
- Distribution stations.

The MV-LV transformation station is usually not included in the vulnerability analysis since, according to the requirements of the majority of national regulations, a hospital should be able to generate power by means of the UPS and EPG systems for a number of days.

An UPS system is typically composed of battery-chargers, inverters, and batteries. By far the most vulnerable component is the battery system located in several cabinets, which may not be anchored to the floor. An example is shown in Fig. 15. Battery failure could occur due to overturning or to impact of adjacent cabinets.

The EPG system typically consists of engines able to generate the necessary power for the functioning of all the essential equipment and furniture. Examples of EPG engines is shown in Fig. 16; a detail of the engine anchorage in shown in Fig. 17. The weakest components of EPG system are the fuel diesel conduits, which usually are not provided by flexible couplings.

The transmission lines of the power network can be generally considered not vulnerable.

The distribution station, including the switchboard panel (Fig. 18), may be a cause of system failure if not properly anchored.

Fig. 15 Example of UPS: Battery cabinet
The generic fault tree of the power system is illustrated in Fig. 19.

![Fault tree of electric power system](image)

The probabilistic description of the capacity of the vulnerable components is given in Table 7.
### Table 7 Probabilistic characterisation of the capacity of the electric power system

<table>
<thead>
<tr>
<th>Object</th>
<th>Demand</th>
<th>Distr.</th>
<th>Mean</th>
<th>CoV</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel conduits</td>
<td>Drift</td>
<td>LN</td>
<td>0.90%</td>
<td>0.25</td>
<td>Kuwataabd Takada (2003)</td>
</tr>
<tr>
<td>Battery cabinet</td>
<td>Acceleration</td>
<td>LN</td>
<td>0.52g</td>
<td>0.62</td>
<td>Swan and Kassawara (1998)</td>
</tr>
<tr>
<td>General switchboard panel</td>
<td>Acceleration</td>
<td>LN</td>
<td>1.12g</td>
<td>0.64</td>
<td>Swan and Kassawara (1998)</td>
</tr>
<tr>
<td>Floor distribution panel</td>
<td>Acceleration</td>
<td>LN</td>
<td>1.75g</td>
<td>0.68</td>
<td>Swan and Kassawara (1998)</td>
</tr>
</tbody>
</table>
2.8.3 Water system

The water system of an hospital typically consists of the supplies, the distribution network (piping) and several equipment such as pumps and boilers. The emergency water supply consists of buried tanks able to guarantee autonomy for a number of days. The equipment should be well anchored and while the piping provided with flexible couplings.

The generic fault tree of the water system is shown in Fig. 20.

![Fig. 20 Fault tree of water system](image)

However, past experiences indicate that pipelines are the real vulnerable component of the water system. An example of piping system is shown in Fig. 21. The probabilistic description of its capacity is given in Table 8.

![Fig. 21 Piping of water system](image)

<table>
<thead>
<tr>
<th>Object</th>
<th>Demand</th>
<th>Distr.</th>
<th>Mean</th>
<th>CoV</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piping</td>
<td>Drift</td>
<td>LN</td>
<td>0.90%</td>
<td>0.25</td>
<td>Kuwataabd Takada (2003)</td>
</tr>
</tbody>
</table>
2.8.4 Conveying system

The performance of elevators in past earthquakes has been satisfactory from the viewpoint of safeguarding passengers. However, damages to its components have often caused functional failure of the system. It is worth noting that the failure of the vertical circulation systems (elevators, escalators and stairs) is particularly relevant since in practice it fatally impairs the functionality of the hospital.

Damage at the elevator systems typically occurs to mechanical components rather than the car itself. Guide rails, counterweights, controllers, machines, motor generators, stabilisers, and their supports and anchorages are the most damaged components during earthquakes (Suarez and Singh, 2000). An example of well-anchored engine is shown in Fig. 22.

![Example of elevator's guide rail and anchorages](image)

Fig. 22 Example of elevator’s guide rail and anchorages

The generic fault tree for elevators is shown in Fig. 23.

![Fault tree of elevators](image)

Fig. 23 Fault tree of elevators

The capacities for these components are difficult to assess: the global criterion by Nuti et al. (1999) has been adopted. The probabilistic model of the elevator capacity is given in Table 9. The functionality of the whole conveying system of a hospital is jeopardised if more than half of the elevators fails.

![Table 9](image)

Table 9 Probabilistic characterisation of the capacity of the elevator system

<table>
<thead>
<tr>
<th>Object (Global criteria)</th>
<th>Demand</th>
<th>Distr.</th>
<th>Mean</th>
<th>CoV</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevator</td>
<td>PGA</td>
<td>LN</td>
<td>0.20g</td>
<td>0.30</td>
<td>Nuti et al. (1999)</td>
</tr>
</tbody>
</table>
2.9 FAULT TREE ANALYSIS OF PHYSICAL COMPONENTS

The relationship between the state of the elements and the state of the whole system is expressed by a fault-tree of the system. The fault trees analysis schematically depicts the components and their functional interrelationship. A basic combination of components consists of a tree-like relationship where the top component is related to its contributing components by “AND” and “OR” gates. An “AND” gate means that the top component is functional (survival state) if all the contributing components are functional (series arrangement), whereas an “OR” gate indicates that the top component is functional if at least one of the contributing components is functional (parallel arrangement).

The generic fault-trees for the sub-components illustrated in previous sections have to be appropriately “assembled” to built up the “system” fault-tree of the whole physical component. A generic fault-tree based on the distinction between essential and basic medical services is illustrated in Fig. 24. Since the fault-tree is hospital dependent, it has to be customized on a case-by-case basis.

The starting point is the identification of areas of the hospital that will house the essential medical services in the emergency configuration. In fact, the emergency layout (i.e. spatial location of the medical services) of the hospital may differ from the everyday one. The required performance for these areas is the Operational Limit State; therefore, it has to be evaluated the response of both structural and non-structural elements. For the remaining areas, a Life Safety performance level is required: the assessment is limited to structural elements.

A preliminary, thoroughly examination of the vulnerable elements is recommended in order to reduce as much as possible the branches of the system fault tree. For example: the principle of hierarchy of resistance may be employed to check the presence of a “weak element” between columns, beams and joints; well-anchored non-structural elements may be eliminated from the fault-tree; etc.

The fault-tree analysis provides a failure/survival response on the state of the medical services (with respect to the performance requirement set for each service). If all medical services survive, i.e. a series system, it is $\gamma_2 = 1$ in eq. (1.1); $\gamma_2 = 0$ otherwise.

The second information derived from the fault-tree is the number of functioning operating theatres, i.e. the parameter $\gamma_1$ in eq. (1.1).

The vulnerability curves for $\gamma_1(IM)$ and $\gamma_2(IM)$ are evaluated by repeating the simulation for different levels of the seismic intensity $IM$, as indicated in section 2.2.
Fig. 24 Generic Fault-Tree for the physical component
3 Organisational component: emergency plan

The organization of the hospital to a hazardous event must be regulated by an emergency plan. A vast literature is available on this subject: (PAHO, 1995), (PAHO, 2000), (PAHO/WHO, 2000), (Pidgeon, 1991) among others.

The lack of this document certifies the inadequateness of the hospital in successfully coping with a seismic emergency. As a consequence, the factor $\alpha$ in the expression of the $HTC$ index (Eq. 1.1) has to be taken equal to nil.

Some basic elements for the evaluation of emergency plan, which may also be useful for the development of emergency plans, are here indicated.

A first check to assess the capability of activating an emergency response consists in the verification of availability and readiness of the following basic items:
(a) medicines and equipment necessary to face the massive incoming of patients;
(b) emergency power generator and emergency water tank necessary to face the possible damages to the external lifelines system.

The stock of medical supplies should include wound dressing, fracture settings, blood, plasma and surgical supplies. Portable equipment has been extensively used in past disasters to increase the number of intensive care beds.

The compliance to the minimum number of days of self-capacity prescribed by national regulations has to be verified. For example: independent emergency power generator systems to guarantee the power supply; buried tank capable to satisfy the water need; etc.

The structural vulnerability of equipment needs also to be assessed, as indicated in previous paragraph.

The hospital should be provided of an efficient emergency communication system, both for alerting all available operators not in service when the earthquake occurs, and for communicating if the normal system fails.

The emergency layout of the medical services has to be explicitly addressed in the emergency plan, with the essential medical services located in areas that satisfy the operational performance limit state.

Under emergency condition, the available resources may be distributed among indoors and outdoors areas. For example, the victims care-path and the essential medical services are typically organised as follows:
(a) **Indoor area**: first-aid zone, triage operation (Red-tagged, Yellow-tagged and Green-tagged zones), Medical services, Pharmacy, Logistic and Hotel services.
(b) **Outdoors area**: gathering of the evacuated patients, parking of ambulance, etc.

The indoor area is subdivided by the triage-codes, with the traffic-light identifying the area for triage. If one area is impracticable due to lack of services or excessive structural or non-structural damage, the green zone will be moved to the outdoors area.
Parking lot and the auxiliary buildings, if present, are useful additional resources that can be used either to gather green-tagged patients or to transfer evacuated patients in case of heavy damage to the main buildings.

The indication on the procedures to active and on who is responsible of what have to be explicitly provided by the emergency plan.

The evaluation of the emergency plan results in assigning a value to the $\alpha$-factor in the $HTC$ index (Eq.1.1). At the current state of development, this is done according to engineering judgment. Typical value may range from 0.5, for very poor emergency plan, up to 1 for an excellent and complete one.
4 Human component: Operators

The evaluation of the Human component involves the assessment of:

a) skill of operators;

b) availability of operators.

The skill is evaluated by expert opinion on the basis of:

- questionnaires;
- weighting the age;
- experience and expertise;
- training and preparedness for emergency response.

The availability of medical personnel affects the actual hospital treatment capacity. It depends on the time of earthquake occurrence: the number of operators is maximum during day-time and minimum at night-time. It is generally acknowledged that, in the European context, the availability of operators is less critical than that of physical resources. However, it is advisable to verify this assumption.

The number of operators for the critical medical services is examined under the most severe condition, i.e. at night-time. The available human resources are compared, for different time-scenario, with the actually needs for the functioning at full capacity of all the critical medical services (assuming full-functionality of the physical components of the hospital, i.e. no damage to structural and non structural elements).

Operators not in service but available at short notice (e.g. ½ hour) can be accounted. In addition, operators may be transferred from non-critical to critical areas under emergency condition (for example, from hotel services to operating theatres).

The evaluation of the skill and of the availability of the operators results in assigning a value to the $\beta$-factor in the $HTC$ index (Eq.1.1). At the current state of development, this is done according to engineering judgment. Typical value may range from 0.5, for poorly trained and understaffed operators, up to 1 for well-trained and adequately-staffed ones.
5 Environment Component

The analysis of the environment component is carried out according to the classification introduced in section 1.1: quantitative accountable elements (Type 1) and non-accountable elements (Type 2).

5.1 TYPE 1 ELEMENTS - SEVERITY INDEX

Epidemiology is the study of patterns of disease and injury in human populations and its application to the control of health problems.

Epidemiologic investigations have identified the causes of injuries due to major earthquake: blast effects, falling masonry, flying glass and debris, and fire. Further, fractures may also result from falls on unstable or slippery footing. Minor trauma generally consists of abrasions, lacerations, and puncture wounds from nails and other sharp objects.

The epidemiology of the injuries provides fundamental information for estimating the type and the amount of the resources needed to treat casualties. An example distribution of patient’s condition, according to the triage classification, is represented in Fig. 25: \( T_1 \) is the % of patients who require immediate care (red tag), \( T_2 \) is % of those who require delayed care (yellow tag), \( T_3 \) is the % of those who needs minimal care (green tag) and \( T_4 \) is the % of deaths (blue and black tag).

![Fig. 25 Example of distribution of patient’s conditions [%]](image)

The casualty distributions assumed by the HAZUS model (NIBS, 1997), and those derived from the 1988 Armenia and the 1995 Kobe earthquakes are illustrated in Fig. 26, Fig. 27 and Fig. 28, respectively.
The medical severity of an event as a function of the patients’ conditions is commonly assessed by means of the following two severity indexes:

\[ S_1 = \frac{T_4}{T_1 + T_2 + T_3} \]  \hspace{1cm} (5.1)

\[ S_2 = \frac{T_1 + T_2}{T_3} \]  \hspace{1cm} (5.2)
The index $S_1$ represents the medical severity of the event, while the index $S_2$ is a measure of the severity of the injuries caused by the event. For the same number of casualties, the larger is the value of $S_2$, the greater is the amount of medical resources that are needed to treat the victims. For example, assuming a casualty distribution as the one shown in Fig. 25, the two indexes assume the following values:

\[ S_1 = \frac{10}{(10 + 30 + 50)} = 0.11 \text{ and } S_2 = \frac{(10 + 30)}{50} = 0.8. \]

The indexes values derived for the (real-cases) casualty distributions shown above are summarised in Table 10.

<table>
<thead>
<tr>
<th></th>
<th>$S_1$</th>
<th>$S_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAZUS (non-collapsed buildings)</td>
<td>0.001</td>
<td>0.194</td>
</tr>
<tr>
<td>HAZUS (collapsed buildings)</td>
<td>0.154</td>
<td>0.625</td>
</tr>
<tr>
<td>Armenian earthquake (1988)</td>
<td>0.575</td>
<td>-</td>
</tr>
<tr>
<td>Kobe earthquake (1995)</td>
<td>0.149</td>
<td>0.261</td>
</tr>
</tbody>
</table>

The results reflect primarily the influence of the environment component, but also the large uncertainties associated with data collection and interpretation. In particular:

- The values reported in HAZUS refer to data inferred from earthquakes occurred in the U.S.A.;
- The data for the Armenian earthquake are representative of the impact of an earthquake on an un-prepared country, where the effectiveness of the rescue operations was very poor;
- The data for the Kobe earthquake (derived from accurate analyses) are representative of the consequences of an earthquake on a rich, well-prepared country, organised to face this type of events.

In general, according to data from past earthquakes, the value of $S_1$ is comprised between 0.1 and 0.5, while that of $S_2$ between 0.15 and 0.6. More information on this subject can be found in (Ramirez at al., 2005), (Shoaf et al., 2000), (De Boer et al., 1989).

### 5.2 TYPE 1 ELEMENTS – CASUALTY MODEL

If epidemiology is fundamental to define the type and the amount of the injuries, casualty models provide an estimate of the global needs of the population. In general, the types and numbers of casualties vary with the characteristics of the earthquake, the building stock in the struck area, the demography and also with the time of the day when the earthquake occurs.

Casualty models provide estimates of the sum of the “severely injured” people (i.e. those requiring hospitalisation treatment) and of the deaths; these are patients identified as T1, T2 and T4 in the previous section. The lightly injured people, T3, are ignored. In particular, the engineering-based earthquake casualty models provide a rapid estimation of the earthquake
impact on population for the purposes of response planning and mitigation. They have typically been developed by engineers from limited, anecdotal, historical data (not from epidemiological studies, nor involving health related researchers). These models are affected by large uncertainties, because there is no agreed definition of when victims may be classified as “injured” (Alexander, 1996). For example, the number of casualties associated to the 1997 Northridge earthquake varies from 5000 to 9000 depending on references.

The casualty model proposed by Coburn and Spence (1992) and simplified by Nuti and Vanzi (1998) is examined. The number of casualties is expressed as a percentage of the population through the following relationship:

\[ C(I) = k(I - I_{\text{min}})^4, \quad (5.3) \]

where \( I \) is the intensity measure of the seismic event, \( k \) and \( I_{\text{min}} \) are the model parameters which take into account both the vulnerability of the building stock and the occupancy rate. These parameters have to be calibrated as a function of the specific environment conditions: according to the model, given an earthquake scenario, the extent of building damage in the affected area is estimated by means of appropriate vulnerability functions.

Naturally, this model is applicable when adequate data about the building stock and its vulnerability are available. In consideration of the large uncertainties that affect the problem, a model error term is included.

The total number of casualties, given as the sum of red-tagged, yellow-tagged, and black-tagged victims, \( N_{T1+T2+T4} \), is given by the following expression:

\[ N_{\text{Cas}}(MMI) = N_{T1+T2+T4}(MMI) = C(MMI) \cdot \varepsilon_{\text{Cas}} \cdot N_{\text{pop}} \quad (5.4) \]

where \( C(MMI) \) is the victims in percentage of the population, \( N_{\text{pop}} \) is the population in the area affected and \( \varepsilon_{\text{Cas}} \) is the model error term.

The model of Coburn and Spence (1992) expresses the \( C(MMI) \) as function of the Modified Mercalli Scale, \( MMI \). The conversion between \( MMI \) and \( PGA \) can be obtained by (Wald et al., 1999):

\[ MMI = 10 + 2.3 \cdot \log_{10} PGA, \quad (5.5) \]

\[ PGA = 10^{-\frac{M_{\text{MMI}} - 10}{2.3}}. \quad (5.6) \]

A log-normal distribution with unit median and coefficient of variation equal to 0.3 may be assumed for the model error term, \( \varepsilon_{\text{Cas}} \).

An example of the casualty curves from the adopted model, evaluated for an hospital located in the south of Italy, is shown in Fig. 29.
Fig. 29 Example of casualty curves

The hospital tributary area can be evaluated by assigning each municipality to the closest main hospital, i.e. among those able to provide adequate medical assistance to serious casualties.

5.3 HOSPITAL TREATMENT DEMAND

The Hospital Treatment Demand, $HTD$, provides an estimate of the number of people that requires surgical attention. It is therefore related to the number of casualties and to the epidemiology of the event.

The $HTD$ index may be evaluated by the expression:

$$HTD = \zeta \cdot N_{T1,T2}, \tag{5.7}$$

where $N_{T1,T2}$ is the number of red- and yellow-tagged patients and $\zeta$ is a factor accounting for the proportion of patients classified as $T1$ and $T2$ which requires surgical attention.

The value of the factor $\zeta$ may vary between $1/3$ and $1/2$ according to experience; the actual value may be defined on case-by-case basis by expert opinion.

The value of $N_{T1,T2}$ can be derived from combining expression of the casualty model (eq. 5.4) with those of the severity indices $S_1$ and $S_2$ given in eq.(5.1) and eq.(5.2). After some manipulation, the numbers of victims subdivided according to the triage codes results to be equal to:

$$N_{T1,T2} = \frac{S_2 \cdot N_{Cas}}{S_1 + S_1 S_2 + S_2}, \tag{5.8}$$

$$N_{T3} = \frac{N_{Cas}}{S_1 + S_1 S_2 + S_2}, \tag{5.9}$$

$$N_{T4} = N_{Cas} \left(1 - \frac{S_2}{S_1 + S_1 S_2 + S_2}\right). \tag{5.10}$$

The final expression for $HTD$ is:

$$HTD = \zeta \cdot N_{T1,T2} = \zeta \cdot \frac{S_2}{(S_1 + S_1 S_2 + S_2)} \cdot N_{Cas} = \zeta \cdot \frac{S_2}{(S_1 + S_1 S_2 + S_2)} \cdot C(MMI) \cdot \mu_{Cas} \cdot N_{pop} \tag{5.11}$$

An example of an HTD curve and of injured-population curves resulting from the analysis for an area located in the south Italy is shown in Fig. 30.
5.4 TYPE 2 ELEMENTS – ACCESSIBILITY AND SOCIAL CONTEXT

The accessibility to the hospital after a major earthquake has to be carefully evaluated. The following element has to be examined:

- distance of the surrounding buildings, i.e. their collapse should not cause damage to the hospital nor limit its accessibility;
- access road to the hospital, both for dimension and connection to nearby highways or major truck;
- heliport.

The social context is intended as the actual recognition at various levels of the society, from authorities to citizens, of the importance that prevention and preparedness to the seismic event play in a positive response of the strategic systems (such as hospitals, fire departments, civil protection, etc.).

At the current stage of development, these "environmental" factors are not explicitly accountable in the evaluation of the seismic risk. However, they are mentioned in this report with the hope of their inclusion in a future development of the methodology. Moreover, they can affect the choice of the severity indexes as well as of the error term in the casualty model that, worth to remember, it is operated according to expert opinion.
6 Summary of the seismic risk analysis

The seismic risk for an hospital system is measured by the comparisons between treatment demand and capacity:

\[ HTD(IM) = \zeta S_0 / (S_0 + S_0S_0 + S_0) - C(IM)\gamma_{cas}N_{pop} \]  
\[ HTC(IM) = \alpha \beta \gamma_1(IM)\gamma_2(IM) / t_m \]  

(5.11)  
(1.1)

An hospital system is made of five components: human, organizational, physical, environmental and medical services. The medical services that have to remain operative after the seismic event in order to guarantee the adequate treatment of patients and victims are classified as essential medical services.

The analysis of the human, the organizational, the environment and the medical services components consists in:

- verifying that the hospital is provided of all the essential medical services;
- assessing the quality of the emergency plan;
- verifying the existence of adequate resources to put into effect the emergency plan;
- assessing the quality of the human component and the availability of the operators to put in practice the emergency plan;
- examining the environment where the hospital is located that affects the number and the typology of victims;

The following data/information are derived:

1. the estimate of the coefficients \( \alpha \) and \( \beta \) in (eq. 1.1);
2. the identification of the hospital areas where the essential medical services are housed;
3. the fault tree of the hospital-system and the fragilities for all the relevant elements at risk;
4. the estimate of the casualty model parameters \( C(IM) \) and of the severity indexes of the event, \( S_1 \) and \( S_2 \) (eq. 5.11).

The numerical analysis of the physical component is carried out employing the probabilistically-based procedure described in Chapter 2. It results in the vulnerability curves of the number of functioning operating theatres \( \gamma_1 \) in eq. (1.1)) and of the system-survival Boolean function \( \gamma_2 \) in eq.(1.1)). The “survival condition” of the physical component is expressed as function of the performance of the medical services, making a distinction between the essential medical services and basic medical services (all the others): the operational performance level is required for the former, a life-safety performance level for the latter. The fault-tree technique is employed for the determination of the state of the system as function of the state of its elements.
References

Bea R., 2003. Lecture notes of CE290A. University of Berkeley, California


Appendix A: taxonomy of Hospital System

<table>
<thead>
<tr>
<th>System</th>
<th>2, Health-care facilities, HCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Critical facility, Point-like</td>
</tr>
</tbody>
</table>
| Notes  | Hospitals represent a particular example of a category of systems that are called “complex-social” systems. From an engineering point of view hospitals are systems made of many components of different nature which jointly contribute in delivering the medical services. These latter represent the system output. From a social point of view, hospitals provide a fundamental assistance to citizens in every-day life; their function becomes of paramount importance in the case of an earthquake event. The medical services, which consist of standardized procedures to guarantee an adequate treatment of patients, are delivered to patients by a joint contribution of the three “active” components of the system: The operators, which are the doctors, nurses and in general whoever plays an active role in providing medical care; The facility (physical component) where the medical services are delivered; The organisation, which is responsible of setting up the adequate conditions so that the medical services can be delivered. In general, this is up to the hospital management through the development, the implementation and the supervision of the standardized procedures. The environment includes all external influences to the functioning of a hospital system, which encompasses such diverse factors as cultural background and soil properties. A performance measure for such system should account for the contributions of all these components to the system services, i.e. \[ PM = f(\alpha, \beta, \gamma), \] where \( \alpha, \beta \) and \( \gamma \) are (random) factors accounting for the human, organizational and physical components, respectively. As state-of-art, an analytical formulation of the above relationship and of factors appearing in it is available only for \( \gamma \) (physical component). Under emergency conditions, the care-path of the victims at the hospital starts with triage and continues with the proper medical operation according to a triage-code assigned to each patient. The understanding of the care-path of earthquake victims allows the identifications of the resources needed for providing health-care under emergency conditions. In particular, the minimum set of medical services necessary to treat victims with serious and critical injuries (yellow and red patients, respectively) results in: diagnostics, surgical treatments and intensive care unit. In addition to the needs of the incoming patients (earthquake victims), those of the in-patients (normal
functioning of the hospital) have also to be considered. A list of the “essential” medical services which are necessary to provide an adequate medical care in an emergency condition, both to the earthquake seriously/critically injured victims and to the in-patients of the hospital, is provided in [Lupoi et al., 2008]. The associated performance requirement is, in the engineering jargon, the “operational” limit-state. Among the essential medical services, the surgical treatment and intensive care unit are by far the “bottleneck” of the care delivery of the hospital. In conclusion, the number of functioning operating theatres is the critical factor to the health-care delivering. Hence, this is taken as the basis of a quantitative measure of the hospital treatment capacity (HTC) under emergency condition.

For all other medical services (i.e. those not included in the above mentioned list), which are referred to as “basic” medical services, it is sufficient to guarantee against the life threat. The associated performance level is the “life-safety” limit state.

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCS01</td>
<td>Organisational Component</td>
<td>The role of the organizational component consists of developing, implementing and supervising all the activities and procedures which have to be immediately activated after a seismic event in order to prevent as much as possible and to promptly recover from the negative impact of the earthquake on the hospital performance. In simple words, this essentially means to set up a sound “emergency plan”. It is worth to emphasise that planning the emergency is the real tool to face the unbalance between resources and needs that develops in the case of an earthquake. Experience tells that a hospital facility which is not provided of an emergency plan will not be able to cope with the emergency.</td>
</tr>
<tr>
<td>HCS02</td>
<td>Human Component</td>
<td>To positively evaluate the response capability of the system, it has also to be checked that simulation of emergency procedure involving both medical doctors and staff have been actually carried out periodically. The human component has to be appropriately trained to perform in a state of emergency, when the operating conditions are physically and mentally much more demanding with respect to normal standard. The capability of the human resources can be assessed only empirically, usually by means of</td>
</tr>
</tbody>
</table>
questionnaires distributed to medical personnel and staff.

The severe target performance set for complex systems or part of them, i.e. to remain operational after a (major) seismic event, requires adequate consideration not only to the "structural" elements of the physical component but also of the "non-structural" elements, which are fundamental to preserve the hospital functionality.

Typical classification subdivides the non-structural elements into three categories: *architectural elements*, *basic installations* and *equipment/contents*.

The operational performance level is related to the response of both structural and non-structural elements, ranging from architectural to medical equipment, basic power and water supplies. The structural integrity performance level is essentially related to the behaviour of the structural elements only.

<table>
<thead>
<tr>
<th>HSC03</th>
<th>Physical Component</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td>The severe target performance set for complex systems or part of them, i.e. to remain operational after a (major) seismic event, requires adequate consideration not only to the &quot;structural&quot; elements of the physical component but also of the &quot;non-structural&quot; elements, which are fundamental to preserve the hospital functionality.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HSC03-1</th>
<th>Structural Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td></td>
</tr>
<tr>
<td>For structural elements local response parameters can be either force-quantities, to evaluate the state of the element with respect to the activation of force-controlled failure mechanisms, such as shear failure (force mechanisms), or the displacement/deformation quantities such as inter-storey drift ratios or chord-rotations, to evaluate the element damage state with respect to displacement-related mechanisms (deformation mechanisms).</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HSC03-2</th>
<th>Non-Structural Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td></td>
</tr>
<tr>
<td>For a non-structural element, the selection of the local response parameter depends on which of the earthquake effects governs its repose. The following major effects are identified:</td>
<td></td>
</tr>
<tr>
<td>• local acceleration, which may cause the element sliding or overturning;</td>
<td></td>
</tr>
<tr>
<td>• structural deformation;</td>
<td></td>
</tr>
<tr>
<td>• relative movements between adjacent or connected structures.</td>
<td></td>
</tr>
</tbody>
</table>
Accordingly, non-structural elements are usually classified as: acceleration-sensitive, deformation (drift)-sensitive or differential displacement sensitive.

In general, a restrained non-structural element is drift sensitive, while a free non-structural element is acceleration sensitive. The differential displacement sensitive elements are those which provide a continuous link across a separation joint or between two different structures.

### Architectural elements

The architectural elements are “typically built-in non-structural components that form part of the building”. Those that have jeopardised the functionality of several hospitals in past earthquakes are: (a) interior and exterior walls, (b) ceilings, (c) windows, glasses and doors.

### Basic Installations

The most disruptive kind of non-structural damage is breakage of water lines inside buildings, including fire sprinklers, domestic water, and chilled-water systems. Leaked water can travel quickly and extensively throughout a building. Second in significance is failure of emergency power systems. The power outage is usually so extensive that reliable backup power is necessary for essential facilities to operate. Others frequently damaged installations, which are essential for the functioning of hospitals, are the conveying and the medical gas systems.

Each of such systems can be subdivided in two main components:

Generation: in an emergency situation, all the essential systems have to be complemented with an internal source. Examples of internal sources are electrical generator, water tank, gas tank. Their typical mode of failure is the damage of anchorages.
### Distribution: pipes for water, for wastewater, for fuel, for gas, and electrical conduits (lines) that run underground or above grade, inside and outside the building. Damage to above ground transmission lines typically occurs along unsupported line sections when lines crack, leak, or fail. Damage to underground transmission lines usually occurs in areas of soil failure where the line sections cannot accommodate soil movements or differential settlements. Damage can also occur when other equipment shifts or falls onto the line, or if a piece of equipment the line is connected to suffers damage. Lines that run across a seismic joint without an expansion joint may suffer damage to their connections or get torn apart.

<table>
<thead>
<tr>
<th>HSC03-5</th>
<th>Basic Installation: medical gas</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Medical Gas Diagram" /></td>
<td></td>
</tr>
<tr>
<td><strong>Medical gas (fixed supply)</strong></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>Bottle</td>
<td>Cylinders</td>
</tr>
</tbody>
</table>

The medical gas system of the hospital consists of the tank and cylinders of the medical gases (oxygen, nitrogen, etc.), the distribution lines (pipes) and several other pieces of equipment necessary to the normal functioning such as, for example, electric pumps.

<table>
<thead>
<tr>
<th>HSC03-6</th>
<th>Basic Installation: power system</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Power System Diagram" /></td>
<td></td>
</tr>
<tr>
<td><strong>Electrical Power</strong></td>
<td></td>
</tr>
<tr>
<td>Normal Building Power</td>
<td>Emergency generator</td>
</tr>
<tr>
<td>MV-LV Transformer</td>
<td>UPS</td>
</tr>
<tr>
<td>Links Transmission lines</td>
<td>Nodes Distribution stations</td>
</tr>
</tbody>
</table>

The power system of a building is usually composed of:
- MV-LV (Medium Voltage - Low Voltage) transformation station;
- Uninterruptible Power System (UPS);
- Emergency Power Generator (EPG);
  - Transmission lines;
  - Distribution stations.

The UPS system is composed of battery-chargers, inverters, and batteries. By far the most vulnerable component is the battery system. The transmission lines of the power network can be generally considered not vulnerable, while the failure of the distribution stations, including the general switchboard...
| HSC03-7 | Basic Installation: water System | The water system of an hospital consists of the supplies, the distribution network (piping) and several equipment such as pumps and boilers. The emergency water supply consists of buried tanks able to guarantee autonomy for seven days, well beyond the three-days minimum prescribed by the national regulations. The equipment have to be well anchored and the piping have to be provided with flexible couplings.

| HSC03-8 | Basic Installation: conveying system | Damage at the elevator systems typically occurs to mechanical components rather than the car itself. Guide rails, counterweights, controllers, machines, motor generators, stabilisers, and their supports and anchorages are the most damaged components during earthquakes.

| HSC03-9 | Building Contents | In a hospital, building content includes furnishings, medical, office and industrial equipment, general supplies, shelves, etc.. Most of these equipment and supplies are essential for the functioning of the facility and for protecting the lives of its occupants, and yet they can represent a danger in case of an earthquake.

Given the essential importance of building content for the effective functioning of the hospital system, all items susceptible to moving have to be properly anchored.