A Knowledge Based Survey of Buildings for Structural Reliability Evaluations

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ABSTRACT

The last disastrous events occurred also recently in Italy, characterised from the collapse of constructions also built in relatively recent, in absence of exceptional actions, have proposed the problem of the dangerousness of great part of the existing building patrimony and the necessity therefore to develop criteria of control of fast type.

As it is well known, in presence of only permanent actions and of those variable ones within the serviceability limits, and excluding therefore causes as the fire, the collision of vehicles or aeroplanes, the earthquake or other natural events of extraordinary entity, have taken place numerous structural failures, also without warning, often arousing a reasonable alarm in the public opinion, to the point to speed up the institution of instruments of law in a position to preventing such catastrophic events. In this paper one proposed methodological of evaluation of the state of structural reliability of a construction is introduced that re-enters in the spirit of performance foretold from such legislative instruments. The proposal is confirmed from one series of useful numerical tests for its validation.

INTRODUCTION – METHODS OF EVALUATION OF THE RELIABILITY OF EXISTING BUILDINGS

The reliability of the existing buildings is a argument of great interest of the present time. The greater part of the existing building patrimony in Italy has been constructed after the second world war and in particular with the building boom around the years ' 70.

During the post-war reconstruction new material as reinforced concrete, without adapted experimental support, has been used. In any case, without taking into consideration the associated cultural or construction aspects that may have conditioned the correct execution of these buildings, it turns out obvious today that we have an increasing number of "obsolete" constructions of more than 40 years. The question rises spontaneous: are such buildings still safe?

The recent landslides happened in Italy, with numerous loss of human life, have confirmed the existence of relative problems of the durability of the constructions. To these constructions the minimal level of performances must be guaranteed, and must be maintained during the entire service life. Since the remarkable resonance of these tragedies, there have been many arguments and debates on avoiding or at least reducing the future landslide probability. The lack of adequate norms that can take part to guarantee the safety of the existing buildings has pushed the Italian government to propose (law design 4339-bis, currently still with to the Italian Congress) "the institution of the issue of the building", an obligatory document for the assessment of the safety conditions. The target is to propose one methodology in order to estimate the emergency of the existing buildings. Such proposal makes reference to various important experiences at international level under the normative and methodological aspects.

Before describing these experiences, it is well to distinguish the building patrimony in two categories: 1) future constructions or of recent edification, for which there exist codified normative instruments that guarantee levels of adapted qualities and safety through design, executive processes, of control and maintenance; 2) existing constructions or of not recent edification, for which the minimal level of safety must be guaranteed.
The various analysed international experiences comprise normative or methodological, in order to guarantee the safety of existing constructions. From the searches a heterogeneous picture turns out rather, in how much every nation has one own "constructive history". But the importance of the successive maintenance aspect to the construction turns out to be obvious. In countries as France and United Kingdom in which, beyond having a control taken care of the construction process through specific responsibilities, low maintenance programs of the realised work. These maintenance programs and the introduction of new professional figures, indicated from recent directives the EEC 92/57, do not make other that to assert one already consolidated constructive structure based on the design and executive quality. Moreover they are present in both countries, even if in various shape, in which a series of data regarding the characteristics of the piece of real estate, comprised all the interventions and the modifications carried out in the course of the years, let alone indications on the state of conservation. These documents are essential in the processes of real estate transition to guarantee future buying.
Also in Italy with the law on the public works n.109/94, following the European Directives, and the recent general regulations of performance introduced with DPR 554/99, has been introduced the plan of maintenance of the building, in which periodic controls are previewed. Unfortunately such norm is applicable exclusively in the realisation of public works and reference to the importance and the specificity of the intervention. Other interesting proposals come from countries with various truths as in the case of Hong Kong. Here the Buildings Department has supplied to the institution of one outline for the inspection of the safety of the existing buildings having an advanced age to 20 years. This control has become necessary considering the enormous state of degradation in which they pour numerous constructions, between which many of "illicit" and therefore not authorised. Of absolute importance is the adopted process of evaluation. One first called phase general evaluation allows control, through visual inspections, the state of conservation of the construction expressing, through a gravity index, the advised interventions. The second phase instead, called detailed control, comes only executed if demanded from before, and more regards an taken care by inspection with successive structural analysis. This logical process of levels allows them to eliminate the cases with little defects in order to concentrate the attention on the more important and problematic cases.
Similar to the process seen for Hong Kong is the one proposed from the *American Society of Civil Engineers* (ASCE) in which are supplied a methodology for the evaluation of the structural conditions of existing buildings in concrete, metal, masonry and wood, through a preliminary evaluation and if necessary through a detailed evaluation. Other specific indications come then supplied from predisposed international norms from International Organisation for Standardisation (ISO), as the ISO/FDIS 2394 and ISO/CD 13822 (rev), in still not definitive writing, in which the criteria come established for the evaluation of the existing structures and serve as a guide for possible national norms. As evaluation methodologies, even if relative to various application fields, they have been shortly described the experiences had from Manfred Wicke (University of Innsbruck) and the Italian GNDT (National Group for the Defence from Earthquakes) of the CNR. The first one has processed a method in order to estimate the state of conservation of the street bridges in reinforced concrete while the second has predisposed a method for the survey of the exposure and seismic vulnerability of the buildings. It does not go then forgotten the issue of the building realised from Rome Administration for the assessment of the static-functional, obligatory consistency for all the buildings and restored every eight years. In such issue a series of

indications goes brought back all that go from the identification to the consistency of the structures carrying until the writing of a synthetic relation in which the technical person in charge to the writing of the issue it proposes to place or less the building under observation. All these norms and methods of evaluation are served from reference for the formulation of the proposed methodology. This proposal has the target create a method of surveying of "speedy" type through which it can be reached to one reliable evaluation on the state of conservation of the construction and debit of the first indications on the interventions to follow.

The process of evaluation, carried out for successive levels, previews initially a preliminary evaluation in order to establish a first approach with the object constructed through the acquisition of a series of identification data and of data obtained from mostly visual inspections or with I use it of simple instruments.

The evaluation method in this phase can be considered of quantitative/qualitative type. It previews a classification of the structural typologies, depending on the constructive system and the used materials, reinforced concrete, steel and wood. To each typology it has been attributed a coefficient, defined as “weight” of the structure (*Ps*), considering the typology in reference to the carrying capacity of the entire structure. The true relief follows, just characterising, for every present structural typology in the construction, the intensity and the extension of the found defects.

The defects are reported to lesions, cracks, gaps, deformations, corrosions, etc., depending on the analysed structural typology. Also in this case they have been assigned of the coefficients weighed to the level of intensity (*Pd*) and extension (*Ps*) of the defect. During the inspecting visit incidental changes of use or structural modifications not authorised or not previewed in the original plan must be verified also, taken into account through corrective coefficients defined as value of use (*Vu*) and value of modification (*Vm*). All this series of weighed parameters serve in order to express the Total Index of Structural Gravity (*It*) that it represents the maximum value between all the Partial Indices of Structural Gravity (*Ip*) founded. The result of the evaluation will be determined from the value caught up from the It index, to which it will correspond one of the six previewed classes of damage. To every class it has been assigned a synthetic judgement that expresses the level of caught up damage and gives the first indications on the advised interventions.

For having then a general picture on the state of consistency of the building evaluation object it is necessary to fill a document, called "Issue of the Building", in which are collected the necessary data for being able to express a judgement of final merit with the indication of the possible successive interventions to take. Moreover such issue will serve as base for future restorations or retrofitting in relation to the interventions brought to the building in the course of the years. Only if demanded from the recommendations of the preliminary evaluation, detailed evaluation have to be executed. This evaluation has the scope to assess the reasons of the endured damage and to establish the current level of safety. To make that, it will be necessary to execute detailed inspections in order to determine the loads, the properties and the strengths of the materials. Structural analyses will be then executed, by means of quasi-probabilistic calculations to the limit states. The results of all the verifications carried out in the detailed evaluation will be attached to the issue of the building.

A METHODOLOGICAL PROPOSAL FOR EVALUATION PROCEDURES

In spite of the variety of the normative proposals and the evaluation methods seen previously it can evidence a not homogenous interpretation of structural safety in the existing buildings, characterised by the common aspects that will serve as base for a methodological proposal of evaluation. An emerged aspect of absolute importance indifferently is that one of the prevention, through plans of maintenance of the work, previewed from the European norm and applied nearly uniform in all the states members. Such aspect but enters in single function

in the case of construction of new buildings or the restructure of existing buildings. Another aspect of common importance is the importance of the role that must assume the customer, leading or owner, as knows the characteristics and the limits of the building in which it is found to living, carrying out periodic inspections of simple execution. It is obvious that as far as the buildings of recent or new construction, thanks to the introduction of more and more severe norms for the execution and quality control of the materials of the constructions, the maintenance programs, turn out more difficult tragic events for unexpected failures.
The problem rises instead for all those buildings, making part of the enormous existing building patrimony, that for several reasons cannot be considered sure under the structural aspect. For such buildings a control and often the improving interventions for guaranty the reliability during their entire life are necessary. The method proposed for the evaluation of the reliability of the existing buildings takes cue from the studied cases and previews a "multilevel" approach.
The base of the process previews a *Preliminary Evaluation* continuation from a *Detailed Evaluation*. The *Preliminary Evaluation* establishes the first approach with the building through the acquisition of a series of identification data and data obtained from mostly relative visual surveys to the state of conservation of the structures. The evaluation method of qualitative/quantitative type supplies a more general definition of the conditions of the structures establishing necessity and priority for a further detailed analysis, if necessary.
The *Detailed Evaluation* is only executed if it is demanded from the recommendations of the preliminary evaluation; further integrating data are collected, relative to the loading actions, to the tests on the materials, the property of the materials, etc., in order then to execute structural analyses through quasi-probabilistic approaches by models to the limit states, with the successive determination of the level of reliability. Subsequently to the evaluation it is written up a issue containing all the relative data of the inspecting visit: identification data, carried out, turned out controls of the evaluations, judgements, interventions, etc. Once compiled such issue will be guarded inside of the building for possible successive inspections.
The exposed evaluation method is applicable indifferently to whichever constructed building and does not take in consideration the pure normative, relative aspects to the modality, to the times of application and the inspecting cycles, that they will be asked to the legislator.

Preliminary Evaluation
The Preliminary Evaluation is identified as the first approach for the verification of the state of conservation of the existing structures. Beyond to a series of data relative to the identification of the building, the constructive and structural systems and the possible present defect in the structure are defined, through visual surveys observations or with simple instruments. The collected information are relative to the defects of surface, deformations, breaches, lesions, corrosions, etc., depending on the employed structural typology. The result of the preliminary inspection are expressed in terms of qualitative judgement through a classification in six levels that expresses the gravity of the damage of the building. To the classification correspond, consequently, the state of conservation and the first indications on the interventions to take. In order to determine to which class belongs a building, reference is made to the Maximum Index of Structural Gravity (*Im*), that expresses the higher value between all the Partial Indices of Structural Gravity (*Ip*) found for every floor. This value takes into account a series of weighed parameters derived from the structural typology, the intensity and the extension of the found defect.

Acquisition of the technical and documentary data
The first data that are acquired are relative to the identification of the piece of real estate. Such data comprise: characteristics of the real estate complex, identification of the manufactured object of assessment second of the historical classifications, presence of not

authorised buildings and over-elevations, modifications of static importance, description of near buildings, the geometric characteristics of the building, location, identification data the real estate units, town technical data, presence of certifications (technical plans, fire protection, load tests, etc), data on planners and constructors, availability of technical documents (original plans, varying, relations, etc). All these data go brought back in the appropriate cards previewed for the issue of the building.

First objective verifications

If the collected documentation is complete one can already have a enough precise idea of the type of building that we go to inspect. In the majority of the cases, for not recent constructions, many data will turn out incomplete or lacking. This does not preclude the goodness of the final evaluation even if lacking data will be listed in appropriate cards to enclose to the final considerations like data to acquire in the successive inspections.

Proposed Methods of Evaluation

The proposed method of evaluation takes cue from the cases examined previously. The introduction of a series of coefficients, attributed for structural typology, intensity and extension of the defect, serves for having the most possible objective and comparable result, independently from the taken building type in examination. The structural typologies have been divided into four great categories: structures of elevation, horizontal structures, covers and stairs. It has been inserted a fifth category relative to other elements, where are inserted divisions or masonry walls, cornices, cantilevers or other structural elements of secondary importance. Such elements, even if not determining, are considered important to the aim of the final total evaluation.

The structural typologies vary with the constructive systems and the used materials, as reinforced concrete, steel and wood. To each typology it has been attributed a coefficient, defined as "weight" of the structure (*Ps*), varying from 1 to 10, that measures the importance of the typology considered in reference to the carrying capacity of the entire structure. During evaluation, this *Ps* value can be varied or adapted according to the characteristics of the structure under inspection. An example of variation regards the structural typologies with a prevailing character, compared with the entire constructive system, as in the case of large span covers or floors.

Defined the structural typologies, we must pass to the description of the defects. The defects are divided in six levels according to the found intensity and express a first qualitative judgement of the state of the analysed structure and the consequences on the carrying capacity and the durability. For each level it has been attributed a coefficient, that it goes from a minimum of 0.10 until to a maximum of 1.00, in order to define the *weight of the defect* (*Pd*), like best evidenced in table 1.

Intensity of the defect	Assigned weight of intensity of defect (Pd)
1 – No defect	0,10
2 – Little defect	0,20
3 – Medium defect	0,40
4 – Severe defect	0,60
5 – Very severe defect	0,80
6 - Total loss	1,00

Table 1: Classification of intensity level of the defect

Another aspect that must be taken into account in order to estimate the safety in the structures is relative to the extension or frequency of the defect. *It* is defined in three qualitative levels: little frequent, frequent and very frequent, like shown in table 2. Also in this case to each level

it is assigned a coefficient that indicates the *weight of the extension or frequency* (*Pe*) and measures, for every found defect, the amount in relation to the extension of the entire structural typology under examination. If the considered defect is quantifiable with an area (es. gap or lack) the extension in relationship to the surface of the analysed structure is evaluated; if, on the contrary, the defect is quantifiable numerically or linearly (i.e. cracks) the frequency of manifestation is measured. In indicative way, the following levels of extension in relationship to the considered surface can be considered: little, not frequent (< 10%); frequent (from 10% to 30%); very frequent (> 30%). This element of evaluation but can turn out complicated when on the same surface can be present more defects, which can be evaluated by extension or by frequency. In this case the appropriated methodology could be to measure the extension of the more serious defect. The *Pe* value in the cases "not frequent" and "frequent" is not always constant, but it varies in relation to the levels of the defect. More a defect is serious and therefore evident, more the value of the extension increases. In this way it has given more importance to the serious but little frequent defects. The coefficients are therefore divided in four groups reported respectively to the levels of intensity 1-2-3, 4, 5 and 6.

Frequency of the defect	**Assigned weight of frequency or extension** (Pe)			
	Defect 1-2-3	**defect 4**	**defect 5**	**defect 6**
A – not frequent	0,45	0,60	0,70	0,75
B – frequent	0,70	0,80	0,85	0,90
C – very frequent	1,00	1,00	1,00	1,00

Table 2: Classification of frequency of the defect

With the aid of survey cards for intensity/extension of the defects and with tables of automatic calculation, that we will see subsequently, it is possible to define with facility the *Maximum Index of Structural Gravity* (*Im*), that indicates the higher value between all the Partial Indices of Structural Gravity (*Ip*). The determined *Ip* for each storey of the inspected building is given from the higher value turning out from the product of the weighed coefficients relative to the defects, to the structural typology and the extension or frequency of its defect. That can be described through a simple formulation:

$$I_m = \max\{Ip_i\} \quad (\text{i} = 1, .., \text{number of storeys}) \qquad (1)$$

$$Ip_i = \max\{Ps_k \cdot Pd_k \cdot Pe_k\} \quad (\text{structure k}) \qquad (2)$$

where:

Psk = weight of the considered structure
Pdk = weight of the defect on the considered structure
Pek = weight of the extension or frequency of the defect
Ipi = partial index of structural gravity (of the single storey)
Im = *Ipi* max = is the maximum value found for the storey

For each structural typology, it is possible to report the specific description of the intensity of the defect found during inspection, with the value of the product of the two factors *Ps* and *Pd*.

As we have seen in previous formulations (equations 1 and 2) the Maximum Index of Structural Gravity (*Im*) gives back a value of gravity of the present damage in the analysed construction. In order to inquire more in deepened way on the real conditions of safety of the structure it comes held account also of the aspect modifications that can have involved of the

variations in the structural conditions. These variations can be relative to the execution of improper works or to changes of destination of use successive to the construction. Therefore two corrective coefficients are introduced defined *Value of use* (*Vu*) and *Value of modification* (*Vm*). Let we see in particular their function.

When it is executed the inspection in order to define intensity and extension of the defects, it is verified also the current destination of use of the storey or the analysed portion of storey. If the use destination is different from that one originally defined or approved of for that type of structure then it will come applied a coefficient of use (*Pu*). This coefficient is only applied to the surface interested from the change of use. The *Pu* coefficient is then standardised in relationship to the entire surface of the storey. The value of use (*Vu*) relative to the storey will be greater than one if the change of use gets worse the loading conditions, minor of one if the change of use reduces the loading conditions previewed in the original plan.
During the preliminary inspection it is always inquired also the possibility of interventions that can have modified or have got worse the structural behaviour of the construction, without that are available relations that certify such modification. Such modifications are classified through qualitative judgements that express the importance of the found modification. An example for absurdity of this variation could be the removal of a pillar, or the opening of a hole of important dimensions in one carrying masonry wall. The definition of a coefficient of modification (*Pm*) reported to the zone interested from the intervention, will go to influence proportionally, following the rules of normalisation seen previously, the value of modification (*Vm*) of the entire one storey. In the following, in table 3, the importance of the intervention and the *Pm* coefficient assigned are reported.

Importance of the structural modifications	**Coefficient of modification (Pm)**
A – not found or not surveyed	1,0
B – of modest entity	1,2
C – of medium entity	1,4
D – important	1,6
E – very important	1,8

Table 3 - Definition of the parameters of structural modification

Class	Definition of the level of the damage and the advised interventions	Value of "It"
Class 1	**No damage or insignificant damage** No maintenance operation is demanded. Probably a lot of the found defects existed already at the moment of the construction of the building or are superficial and they do not interest the structure. No detailed evaluation is required.	**0,00 ÷ 1,00**
Class 2	**Light or little meaningful damage** No immediate maintenance operation is required. The found defects do not modify the safety and the durability of the structures. However the normal maintenance must be executed in order to guarantee the durability and the efficiency in the time of the entire building or portion of it. If the complex of the acquired data turns out sufficiently exhausting in order to recognise the state of conservation in which the building is found it is not necessary to proceed to a further detailed evaluation.	**0,90 ÷ 2,00**
Class 3	**Medium damage** There is no danger for the uses of the building or portion of it, but an extraordinary maintenance operation is necessary, in order to guarantee the durability and the current use of the construction. If the complex of the acquired data turns out sufficiently exhausting in order to recognise the state of conservation of the building it is not necessary to proceed to a further detailed evaluation.	**1,80÷ 4,00**
Class 4	**Severe damage** Immediate interventions of restructure and repair are necessary in order to guarantee the durability and the current use of the construction. It is necessary a detailed evaluation in order to determine the causes of the damages and for verifying the reliability. The possibility of uses of the construction must be verified during the execution of the works.	**3,60 ÷ 6,00**
Class 5	**Very severe damage** Urgent measures are necessary in order to guarantee the safety and immediate interventions of repair in order to guarantee the durability and the current use of the construction. A detailed evaluation is necessary. It is not possible to use the construction during the execution of the jobs.	**5,60 ÷ 8,00**
Class 6	**Very severe damage or total loss** Seen the state in which it pours the construction, immediate interventions of restoration would not guarantee the durability and the use for which it had been constructed. The only possible intervention is the demolition with the reconstruction, if necessary. The damage is so high that no detailed evaluation is required, consisting that it would render such evaluation ineffective.	**> 7,50**

Table 4: Classification of damages of a building

The Evaluation

After the recording in appropriate automatic forms of the data corresponding to the inspections carried out by means of the exposed methodology, the calculation of partial indices *Ipi*, *Vui*, and *Vmi* is carried out. The Index Total of Structural Gravity (*It*) will be the maximum value between the products of the partial indices. Therefore the expression will be:

$$It = \max\left\{Ip_i \cdot Vu_i \cdot Vm_i\right\} \quad \text{(i = 1, ..., number of floors)} \tag{3}$$

$$Vu_i = Pu \cdot Ss/S_i \tag{4}$$

$$Vm_i = Pm \cdot Sz/S_i \tag{5}$$

where:

Pu = Coefficient of use
Pm = Coefficient of modification
Ss = Surface interested from the change of use
Sz = Zone of influence of the modification
S_i = Surface of the considered storey
Vu_i = Value of use of the considered storey
Vm_i = Value of modification of the considered storey
It = Total Index of Structural Gravity

Of course, if the corrective values *Vu* and *Vm* do not find modification to the original loading conditions, the *It* index is equal to the Maximum Index of Structural Gravity (*Im*) seen in equation 1. With the calculated *It* value it will be given a synthetic judgement on the present damage and the advised interventions. Such value will correspond to one of the six established classes of damage, as indicated in table 4.

In the cases in which the value of *It* corresponds to two distinguished classes of damage, the procedure to adopt is to assign however the higher class and to verify their reliability through a general evaluation that takes into account the totality of the collected data.

The *It* index could express a not representative value of all the structure, but only of a storey or one portion of storey. This has had to the applicability of the evaluation method to various constructive typologies that renders impossible to express a medium value or a total sum of products. But at the same time the result reveals the presence of a damage that could

To the end of the evaluation procedure, the result in a single calculation table can be collected several in order to define a diagram of distribution of the partial index of structural gravity referred to the inside of the construction. This table, divided for storey and structural typology, allows to immediately evidence the positioning of the defects and the found degree of gravity. Beyond to the maximum value, it will be possible to formulate a relative average value corresponding to the single structural typology, so as to evidence the degree of manifestation of the damage inside of the same structural typology.

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