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Experience from the use of European Standard EN 1998-3 for seismic assessment and retrofitting – Prospects for the future

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ABSTRACT: To date, EN1998-3 has been applied to few real-life buildings. From the experience gained, three weak points have been suggested: a) assessment criteria concern individual members, instead of the building as a whole; b) depending on the information available, a single "knowledge level" characterizes the entire building and determines a value of the "confidence factor" which is applied indiscriminately on material strengths; c) there are no mechanical models or assessment criteria for nonstructural elements (especially masonry infill walls). The first building retrofitted to EN1998-3 was tested by an earthquake almost as strong as the one for which it had been retrofitted. Ground motion records from the site were used in back-analyses for comparison with the observed performance. The outcome confirmed the general approach of EN1998-3 and its specific rules and criteria, but demonstrated the impact of the lack of attention to nonstructural infills. The paper closes with an overview of the upcoming revision of EN1998-3, in the context of the broadened scope of the second generation of EN-Eurocodes, which includes assessment and retrofitting for all types of loadings.

1 INTRODUCTION

Often structural assessment and retrofitting of a building is triggered by a major refurbishment for change of use, improved energy efficiency, etc. Old building structures may have to be assessed and possibly retrofitted to address:

1. more demanding actions due to change of use/operation, an extension of the design working life, or an increase in loads (e.g., from traffic, changes in the seismic zonation, etc.)
2. deterioration due to environmental effects or due to damage inflicted by accidental actions, such as impact, explosion, fire or an earthquake beyond the design level.
3. requirements set out by authorities, insurance companies, owners, or maintenance plans, especially if the structure has been built according to codes considered in the light of our present knowledge as obsolete and inadequate.

At first sight, any one of these reasons may suffice to question the adequacy of an older building vis- à vis the current requirements for new structures (e.g., those in the first EN-Eurocode generation). The upside is that the simple design models and verifications of the past (and even of the present day) were quite safe-sided. So, their application has normally endowed old structures with considerable safety margins, which help them meet new demands of type 1 to 3 above. To quantify and use these margins, refined analysis methods and models, which are beyond the scope of design codes for new ones, need to be employed for existing structures. This indeed holds in the European Standard EN 1998-3:2005 "Seismic assessment and retrofitting of buildings". Refined models or methods may be adopted also in the upcoming extension of EN 1990 "Basis of structural design" and EN 1992 "Design of concrete structures" to cover assessment and retrofitting under all sorts of actions, and not just the seismic one.

2 OVERVIEW OF EN 1998-3: 2005 AND FEEDBACK FROM ITS APPLICATION

2.1 Introduction

Eurocode 8 "Design of structures for earthquake resistance" stands out as the only one among the first generation of EN-Eurocodes that addresses existing structures – notably buildings. This goes back to the early days when Eurocodes were pre-standards (ENVs), well before sustainable use of construction materials was seen as a reason for retrofitting old structures. This special feature of Eurocode 8 is due to the large size of Europe's building stock which is seismically deficient even in the most seismic parts of Europe, and the threat it poses to public safety.

2.2 Performance objectives, compliance criteria and analysis models

EN 1998-3 follows fully a performance-based and displacement-based approach. Three performance levels (termed "Limit States") are defined:

- "Near Collapse" (NC): the structure is heavily damaged, may have large permanent drifts, retains little residual lateral strength or stiffness, but its vertical elements can still carry the gravity loads. Primary members may reach a safe-sided (e.g., mean-minus-standard-deviation) estimate of their chord-rotation capacity and shear force ULS resistance (the former based on mean material strengths, the latter on design values); secondary members may reach their mean chord-rotation capacity and shear force resistance, computed from mean material strengths.
- "Significant Damage" (SD), which corresponds to "Life safety" and to the local-collapse prevention level for which new buildings are designed per EN 1998-1:2004. The structure is seriously damaged, may have moderate permanent drifts, but retains some residual lateral strength and stiffness and its full vertical load-bearing capacity. Repair may be uneconomic. A safety margin should be provided against the chord-rotation limits that apply to the NC Limit State, but the limit value of shear resistance is the same as in that Limit State.
- "Damage Limitation" (DL), which essentially means "Immediate Occupancy". The structure does not have residual drifts, its elements do not have permanent deformations, retain their full strength and stiffness; and do not need repair. Members are verified to remain elastic in flexure and to meet the ULS shear checks specified for the NC Limit State (see above).

The "Seismic Hazard" levels for which the three Limit States are to be checked are set by National Authorities; otherwise, by the owner. EN 1998-3 itself does not make a recommendation, but mentions that the performance objective recommended for ordinary new buildings is a 225 year earthquake (20% in 50 years), a 475 year event (10% in 50 years), or a 2475 year one (2% in 50 years), for the DL, the SD or the NC "Limit States", respectively. National authorities may decide how many and which of the three Limit States will be checked.

Members are checked in flexure in terms of chord-rotations at their ends. The main aim of the analysis is to estimate the chord rotation demands. Nonlinear analysis – static (pushover) or dynamic (response-history) – is the reference method. It may be applied to all cases, as it can capture certain common idiosyncrasies of existing buildings which are adverse to earthquake resistance and, as such, can be avoided in the design of new buildings. Linear analysis with the elastic spectrum and application of the equal displacement rule at the level of chord rotations is also allowed, if the ratio of the elastic moment to the moment resistance does not vary too much (the recommended range is from 2.5 to 1) among all possible plastic hinge locations.

Secondary members are distinguished from primary ones solely on the basis of their importance for lateral force resistance, without an upper limit to their total contribution to lateral stiffness. They are not exempted from the verifications, but the limits they have to meet are laxer.

Regarding modeling of members, EN 1998-3 is specific and emphatic only about the use of the secant-to-yield-point stiffness as elastic stiffness; for concrete members it also gives information for its calculation, per Biskinis and Fardis (2004, 2010a). Guidance on nonlinear modeling is minimal: essentially, EN 1998-3 only says that the hardening ratio in monotonic loading should realistically reflect the post-yield behavior till the maximum deformation demand, and that hysteresis models − if used − should account for the energy dissipation in cyclic loading.

2.3 *Treatment of uncertainties due to limited knowledge of the as-built structure*

Depending on the data available for the as-built structure, three levels of knowledge are defined:

- “limited knowledge”
- “normal knowledge”
- “full knowledge”.

“Normal knowledge” of the structure's geometry, material properties and amount and detailing of reinforcement comprises all information needed to build a detailed structural model for nonlinear analysis. It is obtained either from original specifications and construction drawings (confirmed for each type of structural member with one material sample per floor and check of dimensions and reinforcement in about 20% of their number) or in-situ measurements (two samples per floor for each type of member and exposure of reinforcement in about 50% of all members). For this level of knowledge, the estimated mean material strengths are modified by a "confidence factor" with a recommended value of 1.2.

“Limited knowledge” can support only a linear analysis model. Default assumptions for the materials may be made based on the codes and the practice prevailing at the time of construction, verified with one sample per floor for each type of member. Simulation of the original design and spot checks in about 20% of the structural members per member type suffice for the amount and detailing of reinforcement. The recommended value of the "confidence factor" modifying the estimated mean material strengths is 1.35.

For “full knowledge”, the confirmation of original construction drawings extends to 20% of the members of each type, and the in-depth survey, when original drawings are not available, to 80% of their number. Material properties are inferred either from test reports at the time of construction, verified with one sample per floor and type of member, or by taking three samples per floor and member type. The recommended value of the "confidence factor" is then 1.0.

2.4 *Main critical comments arising from the practical application of EN 1998-3*

In the few years since the publication of EN 1998-3:2005 and its adoption at national level together with the National Annexes, this European Standard per se has found limited application to real cases. Significant experience has been gained, though, from the application of regulations with strong similarities to EN 1998-3:2005 in Italy (Presidente del Consiglio dei Ministri, 2003) or Greece (EPPO 2011). Certain critical comments have been expressed from the application of the Italian regulation (Pinto and Franchin 2014), which are in tune with the Greek experience:

1. The three "Limit States" are defined for the structure as a whole, but compliance criteria refer to individual members and have to be met by each and every one of them, at least after the retrofitting. It would be more logical to use global criteria instead, at least at the Near Collapse Limit State, and leave some room for judgment, depending on the number, location and importance of non-complying members.
2. The uncertainties considered only concern the materials, the geometry of the structure and the amount and detailing of the reinforcement, depending on the amount of information available. The magnitude of uncertainty impacts the assessment via a universal "confidence factor" applied on material strengths. If materials are less known than the geometry or the reinforcement, or vice versa, it is difficult to assign the entire building to a single knowledge level. Uncertainties should be addressed individually, not collectively, and impact individually any property or aspect affected. Model uncertainties and sensitivity studies reflecting the magnitude of uncertainty should also be introduced.
3. The freedom given concerning nonlinear member models is felt more as lack of guidance and direction. The problem is particularly acute regarding nonstructural elements (especially masonry infill walls), for which even compliance criteria for assessment are lacking.

According to Pinto and Franchin (2014), owing to 1 and 3 above, equally competent designers may reach different assessment outcomes; i.e., unlike design of new buildings, performance assessment of old ones is seen as an analysis problem with a single possible outcome. However, this interpretation may be too narrow: modeling always has a strong subjective component, and engineering judgment is essential. As a matter of fact, in the pilot application of the NEHRP guidelines FEMA 273 for the seismic assessment and retrofit design of 43 real buildings (BSSC 1999), several buildings were studied independently by two US design firms. Retrofitting cost estimates for the same building differed between the two by up to 300%,. This confirms the importance of judgment and shows that lack of an unequivocal outcome is natural.

As we will see in Section 4.2.1, the issues raised by the critical comments above are high on the list of items addressed in the upcoming revision of EN 1998-3. Noteworthy in this respect is the CNR (2013) approach, described and advocated in Pinto and Franchin (2014). This approach is fully probabilistic, accounts for all possible uncertainties arising from the seismic action and demand, the properties and capacities of components, as well as from the model, and addresses the building as a system. It is computationally very demanding, though, because it relies heavily on Monte Carlo simulation. To the extent that it can be simplified without losing its fundamental features, this approach provides very valuable input to the revision of EN 1998-3.

3 FIRST BUILDING RETROFITTTED TO EN1998-3 TESTED BY EARTHQUAKE

3.1 *The background*

The building housing the municipal theater of Kefalonia is the largest in the island's main town. It was designed in 1979 with the 1959 seismic code, for an Effective Peak Acceleration (EPA) of 0.125g (in today's terms). The structural frame of the building was left exposed to the salt-laden environment of the site for over 10 years, without rendering or finishings. The building was completed in the early 1990s. About ten years later, reinforcement corrosion was evident in the perimeter vertical elements. The serious deficiencies of the building raised concerns about its structural safety; the owner was faced with the dilemma of demolition or retrofitting. The conclusion of the seismic assessment per EN 1998-3 was that the building violated the Limit State criteria of Eurocode 8 for an EPA around 0.05g, which is much less than the design EPA specified nowadays in the national code (i.e., of 0.36g). The owner was convinced not to demolish the building, but to retrofit it using EN 1998-3:2005.

3.2 Seismic retrofitting of the building with EN 1998-3:2005

The design of the retrofitting took place in the first half of 2005. Besides cost considerations, there were certain constraints:

- to limit interventions to the exterior and minimise disruption of use during the retrofitting;
- to avoid visible change of the façade;
- to allow only minor changes of the appearance of the two sides of the building.

The main thrusts of the retrofitting were to tackle corrosion of the reinforcement of the exterior vertical elements, especially in the lateral sides, where it was more serious, and to counteract the torsional imbalance due to two large RC walls at the façade. The retrofit design:

- applied one-sided RC overlays on the exterior face of the perimeter vertical elements,
- connected the two structurally independent and torsionally imbalanced units of the building, shown in Fig. 1 (a) and (b), into an integral system as in Fig. 1(c), and
- added two large walls to the back side, counterbalancing the two large walls at the façade.

The nonlinear-response history analyses under bi-directional ground motions scaled to the current design EPA of 0.36g have shown persisting shortfalls in shear in vertical elements which are vital for the stability of the whole; these deficiencies were impossible to correct through RC jackets or overlays, because of limited access to the foundation so as to connect the RC jacket and restrictions in the use of RC overlays at the façade. So, the shear deficiencies were corrected with horizontal Fiber Reinforced Polymer (FRP) sheets, applied on the exterior face of the two large walls at the façade and on the surface of the accessible long sides of two pairs of interior walls. Some deficiencies in shear persisted in the vertical elements of the penthouse and in beams and columns of the façade, especially at the top storey. It was decided not to take further action, profiting from the infills of the frame bays made of thick clay-brick masonry, whose contribution to lateral stiffness and resistance was neglected in the analysis.

The total cost of the intervention, including whatever removal and replacement of wall and floor finishings was needed and 19% VAT, was budgeted to €20 per cubic meter of the building's volume. So, in apparently its first application for seismic assessment and retrofitting of a RC building, EN 1998-3 succeeded to upgrade the building's resistance to ground motions from an EPA around 0.05g to the code-specified EPA level of 0.36g, at a very low cost. Minor deficiencies which could not be corrected without altering the façade or jeopardizing more important elements were tolerated as non-critical for the building as a whole, relying, instead, on the lateral resistance of masonry infills near the deficient elements.

3.3 Computed response vs actual performance in the M6.1 earthquake of 26-01-2014

On January 26, 2014, six-and-a-half years after strengthening works were completed in July 2007, a Magnitude 6.1 earthquake struck Kefalonia. The ground motion was recorded 100 m from the building. The peak ground acceleration was 0.39g in the EW direction, 0.355g in NS and 0.32g in the vertical. Elastic spectral accelerations were well below the design ones in the vicinity of the fundamental periods of the retrofitted building, but well above in the range of the upper natural periods. A nonlinear dynamic analysis was carried out for each one of the two individual as-built parts of the original building under the recorded horizontal ground motions. A large exceedance of the cyclic shear resistance in key load bearing elements (Fig. 1(a), (b)) suggests that collapse would have been a real possibility, had the building not been retrofitted.

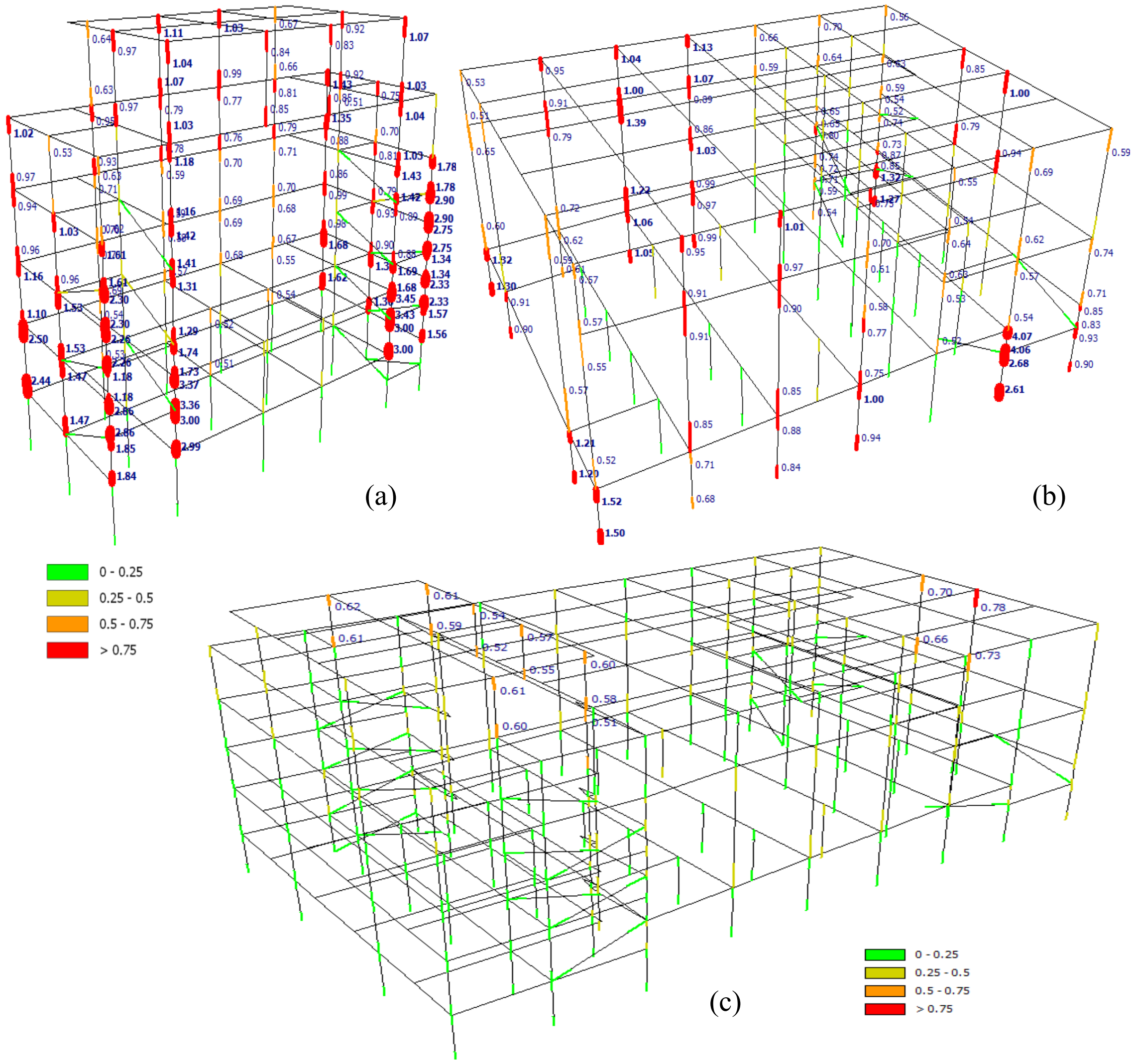

Fig. 1: Ratio of shear force in vertical elements due to earthquake of 26-01-2014 to the shear resistance per EN 1998-3: (a) "Stage" in original structure; (b) "House" of original structure (c) retrofitted building.

Consistent with the analysis of the retrofitted building (Fig. 1(c)), there was no damage to the retrofitted elements or the walls added at the back side. Cracks with residual width of few tenths of a mm were observed in slabs of the roof – suggesting that the corresponding parts of the top slab worked with the roof beams as effective flange in tension – and at the connection of two stair flights with the floor slab or the landing – confirming that stairs take part in the seismic response. The columns around the penthouse, and the top storey beams and columns of the façade were essentially free of damage, confirming that masonry infills adjacent to these elements, but neglected in the analyses, played a beneficial role for the structural frame. The most serious damage was observed at two pairs of masonry infill panels on the sides of the penthouse. These infills were indeed meant to be sacrificed so as to protect the penthouse columns, which were found to be vulnerable and could not be retrofitted without increasing the seismic demands on precarious roof beams supporting the penthouse. Damage to these infills was concentrated around points where systems essential for the operation of the stage were supported. There was also clear evidence of out-of-plane distress of the infills due to their role in supporting these systems. The damaged infill panels were not confined by columns at both ends: they either had a door opening at one end or terminated at a short cross-wall.

So, EN 1998-3 achieved in this case its prime goal: to protect life. More attention should be paid, though, to nonstructural damage, in order to reduce repair costs and disruption of use.

4 ASSESSMENT AND RETROFITTING IN THE NEXT EUROCODE GENERATION

4.1 The context

In December 2012 the European Commission (EC) sent Mandate M/515 to CEN, inviting it to develop a detailed standardization work program for the second generation of EN-Eurocodes, which will include revised versions of the current ones, alongside new Eurocodes. The response of CEN Committee TC250: "Structural Eurocodes" (Denton and Angelino 2013) delineated the scope and the direction of the evolution item-by-item. The work will be carried out in four phases. The first and most important one starts in mid-2015. The last one is planned to finish by 2020, which is the target date for completion of the whole package of new and revised Eurocodes. Phase 1 will include a full revamp of EN 1998-3 under the new title "Seismic Retrofitting of Structures", reflecting the extension of its scope to bridges. New Eurocodes (or a new Section or Annex in the existing ones) will be added, at least to EN 1990 ("Basis of structural design") and to EN 1992 ("Design of concrete structures"), to cover assessment and retrofitting of existing structures against actions other than the seismic.

4.2 The forthcoming new version of EN 1998-3 "Seismic Retrofitting of Structures"

4.2.1 Buildings

Research on seismic assessment and retrofitting has a short history, so scientific technical developments are still fast. Hence, EN 1998-3 needs a thorough update for buildings:

- To rationalize "knowledge levels" and the associated "confidence factors".
- To supplement the current local compliance criteria for member performance with global ones addressing the building as a whole.
- To enhance/update the provisions for nonlinear analysis.
- To enrich/strengthen the part of EN1998-3 specific to masonry buildings, which is much less developed than the one for concrete buildings.
- To revisit/improve areas of weakness, such as the assessment of the cyclic shear resistance of concrete and masonry elements, the seismic behavior of walls and floor diaphragms, etc.
- To cover the facility as a whole, including its nonstructural components and equipment.
- To update the technical information on retrofitting techniques, in the light of recent developments (e.g., Biskinis and Fardis 2013a, 2013b, Fardis et al 2014, Biskinis et al 2015).

4.2.2 Bridges

Most transportation networks in Europe predate seismic design codes for bridges. Bridges not designed for earthquake resistance pose a serious threat to the operation of a network after a strong earthquake. Some national authorities have launched seismic evaluation campaigns of old bridges and have even undertaken their retrofitting. To support such national efforts, EN 1998-3 will be extended to cover seismic assessment and retrofitting of bridges.

Strengthening the foundation of a bridge is a serious technical challenge, which often sets a limit to the upgrading of the lateral force resistance of the piers. So, seismic isolation of the superstructure and/or supplementary energy dissipation devices at the interface between the superstructure and the top of the piers and/or the abutments hold great promise as a means of seismic retrofitting and will be prominent in the extension of EN 1998-3 to cover bridges.

4.3 Prospects for the assessment and retrofitting of structures for non-seismic actions

4.3.1 The rationale

The initiative to address existing structures in the second generation of EN-Eurocodes serves "Basic requirement" no 7 for construction works: "Sustainable use of natural resources", which was added when the European Council's Construction Products Directive was upgraded to a Regulation of the European Parliament and the Council (EU 2011). Sustainability is promoted by retrofitting existing facilities to meet today's needs in lieu of demolishing and building anew.

4.3.2 The evolution of EN 1990 to encompass existing structures

For the evolution to the second generation of EN-Eurocodes, the fundamental requirements and principles in EN 1990 "Basis of structural design" will be extended to existing structures, taking into account the difference between assessment and retrofitting of old and design of new structures. This extension will cover all types of structures and construction works (including geotechnical ones) under all kinds of actions except the seismic, which will stay in the realm of EN 1998-3. An indication of the framework and contents of such an extension may be found in Part III of the recent draft of a JRC Scientific and Technical Report (Luechinger et al 2015). After approval by CEN/TC250, Part III may evolve into a CEN Technical Specification, which may later form the basis for the part of EN 1990 devoted to existing structures. The rest of the present sub-section gives an overview of Part III in Luechinger et al (2015).

Unlike new structures, for which national authorities specify the safety and performance objectives through the National Annexes to the Eurocodes, for the assessment and retrofitting of existing ones the owner may share this responsibility with the competent authority. A third option has been added to the usual requirements for life safety (Ultimate Limit State) and serviceability, namely continued operation of essential facilities or infrastructures despite a hazardous event, such as an earthquake or impact. Means are provided to allow selection of the target reliability for life safety as a function of the intended remaining working life of the facility, the acceptable level of risk to persons, the use and size of the facility, as well as economic considerations, in view of the fact that a certain raise in the safety level costs much more if it is attempted a posteriori for an already built structure (especially if the indirect cost of the disruption of use is included), than when it is done for a new one at the design stage. It is also explicitly stated that the codes applicable at the time of the original construction can only be used as a source of information for an old structure, not as a basis to consider its safety level acceptable: old codes may be technically questionable and not relied upon anymore.

Once the performance objectives are set, the actions, environmental conditions, etc, foreseen for the intended remaining life of the structure are set out. The characteristic values of variable or climatic actions may be estimated accordingly, as well as the evolution of any deterioration phenomena. The next step may be a preliminary assessment; comprising a study of the available documents, a visual inspection of the structure and its condition, and preliminary checks aiming to identify critical deficiencies. Its outcome may include decisions to implement immediate safety measures, to mitigate imminent hazards or to reduce their potential impact (e.g. to evacuate the facility); it may also include a plan to carry out detailed investigations focusing on critical deficiencies. It may be decided to carry out a detailed assessment, comprising a search for further sources of information and their study in detail, a thorough inspection and documentation of the present condition of the structure, material sampling and in-situ and/or laboratory tests, etc. The extent of in-situ sampling should be judiciously chosen, to balance the gains from the information obtained against the costs incurred and the damage inflicted on the structure by sampling. The new data should be used together with prior information in order to statistically derive/update characteristic values of material strengths, permanent actions, etc. A critical issue is to identify if there are more than one statistical populations in the structure and to estimate their statistical parameters accordingly.

More refined analysis methods and models than those typically used in new designs may be employed. The partial factor method is retained for the verification format, if linear analysis is used, while the global resistance factor approach is preferred for nonlinear analysis. Expressions and tools are given for the calculation of partial or global resistance factors from the estimated parameters of the pertinent action or material variables. Model uncertainty factors are foreseen. The method and the model should be checked, validated or calibrated by carrying out an analysis of the structure in its estimated current condition under the actions estimated to have taken place in its hitherto lifetime; the outcome (safety level, deformations, etc) of such an analysis should be compared with the actual performance to the present date.

Decisions to be made on the basis of the outcome of the assessment may include:

- decommissioning of the facility,
- emergency safety measures (shoring, evacuation, restrictions in use, reduction of loads),
- acceptance of the current condition (possibly for a reduced remaining working life) alongside the establishment of a monitoring and maintenance program,
- repair or replacement of damaged/deteriorated components, or
- upgrading to meet the specified performance objectives.

A procedure is also described, alongside the conditions for its application, to carry out an assessment based solely on the satisfactory past performance and serviceability of the structure.

In summary, the approach being adopted promotes flexibility in the overall procedure and strives to balance pragmatism with scientific/technical rigor. It is inspired to a certain extent by EN 1998-3:2005, but at the same time opens new roads and brings fresh ideas, from which the evolution of EN 1998-3 to its second generation version will certainly profit.

4.3.3 The evolution of Eurocode 2 (EN 1992) to encompass existing concrete structures

Eurocode 2 (which, in the second generation, will cover in a single part the general aspects, buildings, bridges, containment structures, etc) seems at present to be the only one of the seven material Eurocodes to cover assessment and retrofitting of existing structures.

An important work item will be to check the models used in design of new structures: for the materials, their interaction through bond and the resistance of components. In some cases current design models may be considered applicable to existing structures as well; in others, new models may be needed. For instance, new models will need to be introduced for damaged or degraded components, for corroded bars and for the members containing them, for the increase in member flexural resistance thanks to membrane forces produced by a restraint of the member's axial deformation, etc.

A second important work item concerns the use of Fiber-Reinforced Polymers (FRPs) for strengthening of concrete structures. The intension is to cover conceptual design of retrofitting using FRPs, and to introduce design models for the behavior of FRP-strengthened members at the Ultimate and the Serviceability Limit States.

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