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A PRACTITIONER'S PERSPECTIVE ON THE BENEFITS AND SHORTCOMINGS OF THE USE OF NONLINEAR ANALYSIS FOR THE SEISMIC EVALUATION AND REHABILITATION OF EXISTING STRUCTURES

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ABSTRACT:

The idea of using nonlinear analysis for the seismic evaluation of structures became a goal early in the development of earthquake engineering, after the acknowledgement that nonlinear behavior of structures had a major impact on their seismic response. The practical application of nonlinear analysis, however, had to wait until reasonable consensus was gathered regarding the adequate methodologies, computers were powerful enough to carry on these more complex analyses, and enough data was collected to reliably model different structural components in a non-linear fashion. We are seeing now that all three aspects are materializing and, consequently, the use of nonlinear techniques for the seismic evaluation of structures has become viable.

This paper addresses the benefits and shortcomings found during the implementation of this technique in actual seismic evaluation and rehabilitation projects, and it is built upon the experience gained in numerous projects conducted by the authors in the last few years. It was found that the greatest benefit is that the insight into seismic response gained using this tool far exceeds what a linear-elastic analysis can deliver. There are however difficulties that need to be dealt with carefully, such as the extent of the effort to create a reliable nonlinear model, and deficiencies in current guidelines. One of the major problems with current guidelines is that they were not thoroughly developed using a "nonlinear" mindset which, was found, may have serious consequences in the implementation of a project of this type. Another substantial challenge with complex nonlinear analysis is the difficulty in validating computer results with a "gut feel" using simple engineering tools. The paper elaborates on these and other aspects brought about by past experience of the authors with projects of this type.

KEYWORDS:
Non-Linear Analysis, Performance Based Design, Seismic Retrofit, Existing Structures.

1. INTRODUCTION

It is generally accepted that structural systems should be designed to sustain seismic demands with a controlled amount of post-elastic behavior. This concept, which is incorporated in our current seismic design standards, is based on the belief that the structures will be able to develop certain level of ductility if prescribed detailing conditions are met. Such detailing conditions are embedded in our codes and any new structure designed to current standards should meet them.

It is then justifiable that, when the details that afford the structures this post-elastic capacity are not present, the structure should be dealt with in a conservative way that, at the core of the procedure, prescribes low or no post-elastic capacity for the structural components. This is the conventional way to deal with the seismic retrofit of existing buildings, and it is the way it was first implemented in buildings codes.

Unfortunately there is still a vast stock of structures that were not conceived with the seismic concepts that we acknowledge as important today. Structures built before the 1970's were mostly designed to sustain seismic demands not too different than static loads. Ductility was not recognized as the vital aspect we now understand it to be for the survival of a building subject to seismic loads. Efficient collapse mechanisms where not considered. Complete load paths were not a major concern.

Consequently, it is very common to find pre-1970 buildings lacking key seismic features that we routinely incorporate in the design of new buildings. The retrofit of these pre-1970 buildings presents a difficult challenge to the designer, and not surprisingly leads to the implementation of retrofit solutions relying heavily on new structural components and, many times in the process, neglect the contribution of existing ones.

The authors have found that nonlinear analysis may be a powerful tool for the evaluation and retrofit design of such buildings. Numerous benefits have been identified in the implementation of such a tool, but difficulties and challenges also abound. Below, the authors discuss the benefits and challenges encountered in the process, as well as recommendations when using this tool.

2. BENEFITS OF THE USE OF NONLINEAR ANALYSIS FOR THE RETROFIT OF EXISTING STRUCTURES

The use of nonlinear structural analysis is well suited for the seismic rehabilitation of existing structures which have been engineered without the seismic principles that we currently acknowledge as desirable. A discussion of some of the most significant benefits follows.

2.1. Ability to explore actual post-elastic seismic performance of existing structures

Nonlinear analysis permits the exploration of the post-elastic behavior of a structural system not inherently designed to behave as such, but that may potentially be efficiently modified for that purpose.

Although one may think that demand/capacity ratios obtained using a conventional linear elastic analysis could be a reasonable way to estimate overall or local ductility demands, this is not entirely true if one factors in the redistribution of internal actions after one or many individual structural components start reaching their strengths. This is more the case in irregular structures. Current standards tend to rely greatly on these D/C ratios as a means to control the ductility of existing members.

Learning the post-elastic seismic response of the structure is an important insight that if conducted early enough in the evaluation process will pay off greatly with a convenient retrofit solution. It is important, however, not to rely heavily on the model as the variability of the constitutive parameters is large. Therefore, an effort should be made to conceptually understand why the model is behaving as displayed, as well as to verify if basic equilibrium principles are met.

2.2. Better identification of adequate collapse mechanisms for the existing structure

A nonlinear evaluation of an existing building is a powerful tool for better understanding of the collapse mechanism that more efficiently can be forced in a building via deliberate retrofit actions. Learning how the structure tends to behave after its constitutive components start reaching their strengths allows a more sensitive and potentially less invasive retrofit solution.

The authors have experienced that the identification of the most appropriate collapse mechanisms for an existing structure is not a trivial task, and having a simple nonlinear model of the building helps visualize the options one should consider as candidates for a final desirable collapse mechanism for the structure.

Having an understanding of the collapse mechanism is in itself a huge improvement from the conventional linear elastic approach.

2.3. Better identification of efficient retrofit options

Only the exploration of the post-elastic response of a system that does not have an intrinsic seismically efficient collapse mechanism can give the designer the appropriate insight to propose a retrofit solution that is not excessively conservative.

Understanding of the post-elastic response, as limited as it may be, permits a more focused treatment of the retrofit of the structure.

Current codes tend to deal with the uncertainty in the post-elastic response of structural systems limiting the ductility of the structural components and thus forcing severe strengthening actions that in many cases lead to a dismissal of the existing components and detailing of new code-compliant elements. The result of this approach is often invasive retrofit solutions that not only are costly but may have a severe impact on the function of the building and, in many cases, on adjacent structures that need to be also modified to accommodate section enlargements or new elements designed as part of the retrofit plan.

The authors have found that not all structural components are equally relevant for the overall seismic performance of the structure and that the identification of these critical components sometimes can only be reached using nonlinear analysis. Furthermore, the authors have found that, once the appropriate collapse mechanism is determined, it is even desirable to allow certain components to fail early so that the mechanism is more easily induced.

2.4. Improved communication of the expected performance of the buildings

Even though nonlinear models are much more complex than linear elastic models, the overall results are easier to communicate as they depict the actual state of the structure as it is subjected to increasing seismic demand. A model showing plastic hinges as they are formed, or walls failing in shear or flexure can tell much more than a wordy explanation of the expected collapse mechanism of the building.

When communicating the expected seismic performance of the structure, however, the description should be supplemented by a thorough explanation of the implications of the observed damage, as it most likely would bring attention and concern if not properly understood.

2.5. Potential reduction of retrofit costs

An important consequence of reaching an efficient seismic retrofit solution is a potential reduction of the retrofit costs. Using the capacity of the existing components, combined with an appropriate selection of an efficient collapse mechanism should lead to a reduced retrofit cost. The authors have observed cost reductions of the order of 50% or more when comparing retrofit solutions based in conventional linear elastic models with solutions based on nonlinear analysis.

2.6. Potential reduction of disruptions due to retrofit work

The cost reduction is not only experienced in less retrofit work but also in less impact on the day to day operations conducted in the building. In many cases disruptions can be as or more costly than the direct retrofit cost itself.

3. CHALLENGES AND SHORTCOMINGS

As appealing as it may be, the use of nonlinear analysis is not an easy choice to make as challenges abound in the process. The authors discuss below some of the challenges and difficulties one may face.

3.1 Conveying the extend of the expected outcome may be difficult

The expected seismic performance of a building is poorly understood by lay people. Even we structural engineers do not fully grasp what does having a code conforming seismic structure means for the performance of the building. Lay people may rightfully expect that a seismic design should lead to avoidance of significant damage to the building. We know however that the basic goal of most seismic codes is to provide a life safe structure, which won’t collapse but that may have significant damage.

When one follows a conventional linear-elastic based procedure, the usual description of the outcome is that the structure will meet the seismic prescriptions of the seismic code. Most times this declaration is reassuring enough for an owner.

However, when following a nonlinear based procedure, the performance objective has to be explicitly described. It could be difficult for an owner to acknowledge that the life safe structure he/she would get after the retrofit is expected to sustain significant structural and non-structural damage. And maybe once the performance is understood, and it could be ugly, the life safe objective may not be that comforting any more.

The challenge is therefore to be sensitive to the needs of the owner, and to be able to target the process so that these needs are met successfully.

3.2. Overall greater effort for implementation

As discussed above, implementing a nonlinear based retrofit process may lead to a significant reduction in the final retrofit cost, however, the initial investment may be substantially higher than in a conventional linear-elastic based procedure.

Implementation of nonlinear models demands an effort significantly greater than the required for the implementation of linear elastic models. This effort is reflected in resources as well as time spent, and not everybody is prepared for it.

There are not shortcuts in the process. At best, the process could be staged so that the potential benefits of the procedure, or the lack of them, can be anticipated, weighed, and the decision to sustain the effort can be made.

The expanded effort can be very taxing for an owner. This presents a major challenge for the structural engineer and demands a candid assessment of the probable final benefits of the process, as well as a coherent explanation of the level of commitment required to successfully implement this choice.

The greater effort is not only of the structural engineer in charge but also is extended to the involvement of other design professionals whose participation is limited otherwise.

3.3. Potential need of major component/system testing

The last 20 years have seen the development of guidelines and standards for the modeling of structural components as well as extensive appropriate methods that can be implemented without much controversy. However, the methodologies proposed in the above mentioned guidelines and standards are sometimes not comprehensive enough and, as expected, do not cover every component type or condition found in an existing structure.

Many times the best option is the explicit testing of critical structural components. Testing allows the designer to abandon excessively conservative assumptions that may limit the potential of the nonlinear structural evaluation. But it may also be seen as an additional burden for the project.

The authors can attest that, if conducted properly and with the right advice, component testing may substantially enhance the ability to select the right retrofit option and the confidence of the design team on the selected retrofit solution.

3.4. Nonlinear analysis is often conducted with a linear elastic mindset

Even though it has been at least 10 years since nonlinear analysis was started to be used as an alternative tool to linear-elastic based procedures, many of the current rules for implementation of nonlinear based seismic analysis are still based on rules developed for linear elastic procedures. To illustrate this, the authors would like to focus in one particular condition below.

One of the most useful (and perhaps less appreciated) aspects of linear elastic modeling is the possibility of extrapolate and/or superimpose results of loading conditions. In linear elastic systems running a live load, dead load and seismic case, is enough to produce a variety of loading combinations amplified or reduced, oriented in the same or reverse directions.

When nonlinear behavior is expected, however, such combinations are not possible. Every relevant combination has to be implemented as a different run. As a result, one may end up with a long list of cases to run individually, which if one notes that nonlinear runs can take significant time (the authors have had to run single cases for about 4 days) the task may be impractical, if not impossible.

This shortcoming may be further exacerbated, if one takes into account that current standards require combinations similar to those required for linear elastic conditions, without the benefit of the superposition of loads. The authors have found that if current guideline's rules are followed, the use on nonlinear analysis would be impractical in most cases.

3.5. Post-elastic seismic response could present insolvable modeling problems

Many times the authors have had to face insolvable modeling problems. Even though the last 10 years have seen an explosion of powerful commercial nonlinear analysis programs, their modeling capabilities are still limited. The authors think that this actually may be a good thing as it forces simplification of the problem and prevents the always tempting path of excessive modeling detail. However, one will certainly find important conditions that are beyond the capabilities of current commercial software.

A problem commonly found by the authors is the determination of ductility and strength properties in elements where these parameters depend on axial load. Although many commercial programs can handle the flexural and shear strength of frame elements as a function of the axial load, the authors are not aware of software capable of capturing such variation in wall segments. The variation of ductility as a function of the axial loads is also conspicuously absent in commercial analysis software. In this particular case the authors had to pick a single condition to represent the range of expected variations in the seismic response.

This is one of a few important modeling issues that may have to be dealt in a simplified way or incorporated in the new generation of nonlinear modeling software.

3.6. Occasional difficulty bounding the expected seismic performance

The feasibility phase of a seismic evaluation should ideally conclude with the determination of worst and best expected seismic performances. These scenarios would help determine the value of embarking in a comprehensive non-linear based retrofit design. There are cases, however, when the authors have observed that the bounding of the expected outcome is difficult to achieve. Sometimes it is due to the a systemic sensitivity to one or many parameters or to the excessive variability of certain parameters.

3.7. Danger of missing the big picture

When performing nonlinear structural modeling, it is easy to get dragged into excessive modeling detail. It must be understood that the exact modeling of the structure is impossible. Significant effort could be wasted trying to model aspects that may be irrelevant to the overall seismic response of the structure, or modeling conditions that are themselves affected by other aspects which are poorly understood and therefore loosely modeled. A balanced model therefore should be sought.

The balanced modeling is not only referred to the numerical model of the structural components only, but also refers to the modeling of the ground motion demand or other geotechnical aspects relevant to the seismic performance of the building.

4. CONCLUSIONS AND RECOMMENDATIONS

The authors have the following conclusions and recommendations for other practitioners involved (or interested) in nonlinear analysis based retrofit design.

- A nonlinear model has the potential of greatly improving the understanding of the seismic performance of existing structures. The nonlinear model, however, must be seen only as a tool and not as a goal in itself. The number of parameters affecting the overall response and the range of their variation makes it impossible to model an exact response.

- The authors would recommend remaining focused on the understanding of the post-elastic response of the building. If such behavior is not understood, the option of using nonlinear analysis should be revisited.

- Very irregular buildings may be bad candidates for this evaluation process, and although it is possible to force a stable post-elastic response within a range of load conditions, the authors have found that important aspects such as identification of load paths or identification of potential critical structural components are not easy to achieve.

- Component testing should be considered. Current guidelines and standards do not cover all conditions and could be very conservative in the definition of the expected post-elastic response of structural components.

- The authors have found that the nonlinear modeling of structures should be implemented initially to help understand the seismic performance of the subject structure. Then, after a reasonable insight of the seismic response has been gained, and a desirable mechanism has been selected, the model should be used to test different retrofit solutions that would lead to this desirable final condition. The ideal outcome of the process would be a retrofit solution that leads to a seismic response nearly insensitive to the variation of modeling parameters within the expected variation range.