Nonlinear Dynamic Response of Reinforced Concrete Buildings and the Effect of the Directionality of Seismic Accelerations: An Innovative Structural Analysis Program

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The security of a nation implies having a complete overview of all possible risks, and since time immemorial, humanity has known about the rare but inevitable seismic risk. History serves as a reference to establish how catastrophic an earthquake can be for a region where its inhabitants do not take precautionary measures to face this natural event resiliently. In the United States, the 1994 M6.7 Northridge earthquake in California remains the third costliest disaster in U.S. history; and it was one of the most expensive disasters for the federal government (FEMA, 2017). The entire west coast of the continental United States, the south coast of Alaska, Hawaii, and Guan, over twenty-three thousand miles of coastline, are identified as very high risk areas by the USGS (FEMA, 2016). Puerto Rico and the Virgin Islands are categorized as high and moderately high seismic risk, although recent technical studies indicate that the risk could be underestimated. This study develops a program to model the behavior of reinforced concrete structures during an earthquake and will be used to study the effect of the directionality of seismic accelerations, in order to provide an alternative to understand better the interaction between essential components of our infrastructure, buildings, and these natural phenomena. As the knowledge of structural performance during earthquakes is improved and tools that can be used during design are added, we will move towards safer and more resilient communities.

Methodology

To synthesize the methodology of this work, will first present what is related to coding the analysis program in terms of programming and computational capacity. The analysis program is coded in two main parts: a computational executor and a graphical user interface (GUI). Everything related to the analysis calculations is coding in the Fortran programming language, using the standard adopted in 2010 (ISO / IEC, 2010). This language was selected for its characteristics of computational speed and numerical precision (machine epsilon = 1.92×10^{-34}, zero in logical comparisons = 1×10^{-33}) and is a widely known language in the field of science and engineering. The GUI is built with the Visual Basic 2017 coding language as an MS Windows Forms App with .NET Framework 4.6.1. In summary, compatible with the vast majority of current Windows OS computers with 64-bit CPUs.

The structural analysis model is based on the typical three-dimensional cartesian coordinate analysis environment where nodes are defined and linked together with elements to simulate structural elements' behavior. The nodes are characterized by their three coordinates, associated mass, and six degrees of freedom (DOF) (three displacements or force and three rotations or moments). Elements are defined by up to 85 parameters and a diagram to define geometry and steel reinforcements' location in their cross-section. The main behaviors of non-linearity and inelasticity of reinforced concrete structures are considered through the parameters that define the elements. The definition of floor slab-type elements that maintain elastic behavior is included as special elements. Once the structure's geometry and the mechanical characteristics of its components are defined, the analysis model simulates the building's nonlinear inelastic dynamic response. Figure 1 is a synthesis of the model.

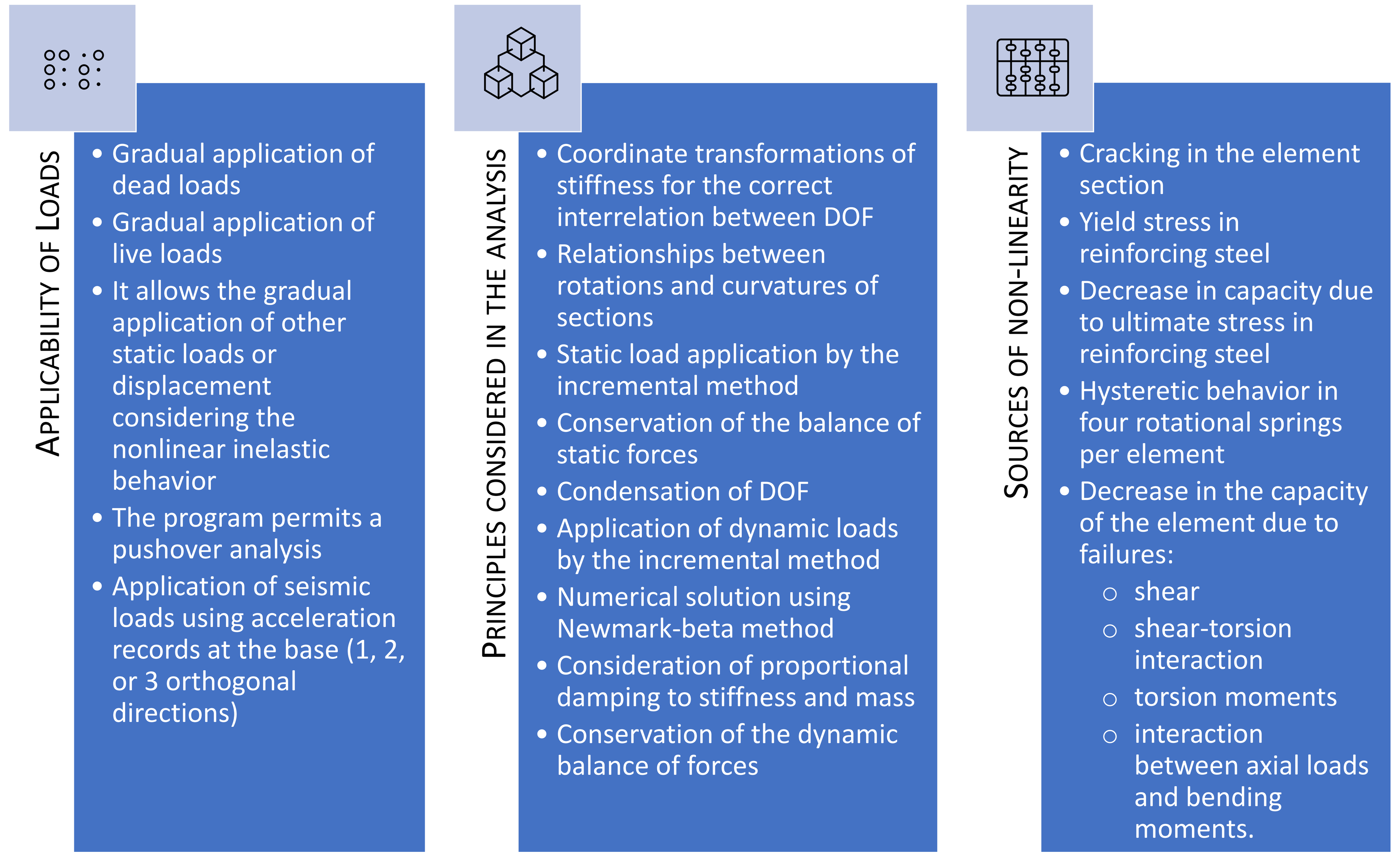

FIGURE 1: Key elements on the analysis model

Once the analysis program is completed and validated, it will be used to model different buildings designed according to current building codes, to contrast the response before different incidence scenarios of seismic accelerations in terms of the directions. The idea is to make the applied acceleration records orthogonal directions that do not match the elements orthogonal axes and the frame arrangement, which are typically defined during design.

Outcomes

The present research is undergoing; the phase where the structural analysis model is defined was completed, and its mathematical execution was coded. The GUI was prepared, and dozens of analyses were carryout to validate the model. Figure 2 shows some example screenshots of the analysis program (alpha version). In the process, inclusions have been identified to improve the analysis model. Additional considerations for shear deformations were added, the possibility of rigid segments in the elements was included, and mathematical operations were reformulated for better computational efficiency. This reformulation had a significant impact on the execution time of the analysis since, by the nature of the model, it is required to solve systems of equations with several hundred unknowns continuously for thousands of times. The new version solves 76% faster for gradual application of static loads and 32% faster for the base accelerations' analysis. This work is currently in the validation phase of the new version to start analyzing and studying the change in seismic performance influenced by the directionality of seismic accelerations.

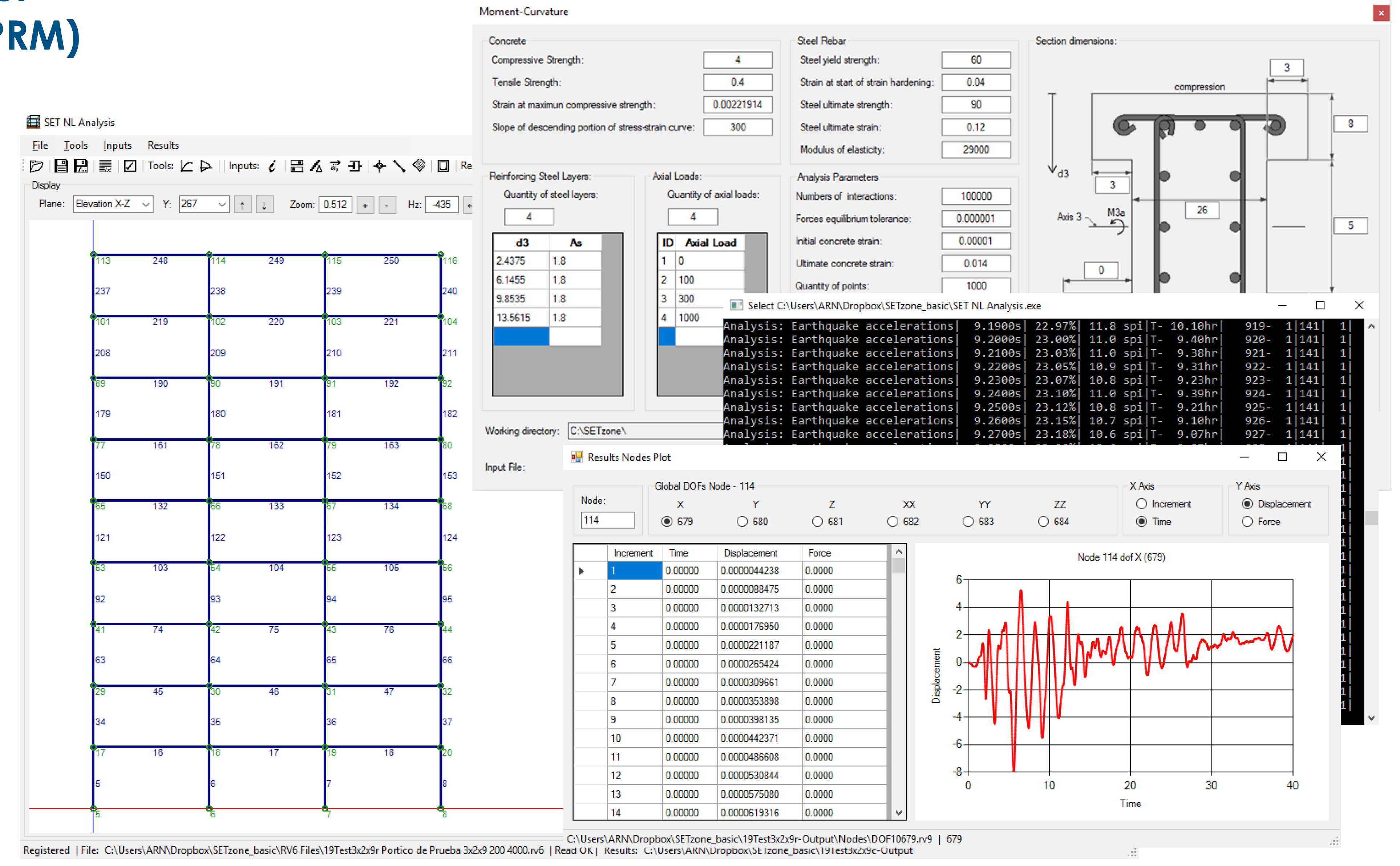

FIGURE 2: Examples screenshots of the analysis program (alpha version)

Conclusions

This research is not yet at the stage to issue conclusions. However, it is expected that a new tool will be obtained that will serve for future works and designs. This tool has more flexibility for the inclusion of parameters and methodologies than commercial programs, which do not offer access to their source code. It is expected that the study of comparative performances between different incidence scenarios of seismic accelerations in terms of the directions will serve to issue design recommendations to complement currently used analysis methodologies. This work's ultimate goal is to improve our infrastructure's resiliency, protecting the life, safety, and property of hundreds of communities in seismic risk areas.

Acknowledgements

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References

American Concrete Institute, (2014), "Commentary on Building Code Requirements for Structural Concrete (ACI 318R-14)" / "Building Code Requirements for Structural Concrete (ACI 318-14)", ISBN: 978-0-87031-930-3

Chapra, Steven C. , Canale, Raymond P. , (2009), "Numerical Methods for Engineers, 6th Edition", McGraw – Hill Primis, ISBN: 0-39-095080-7

Chopra, Anil K. , (1995), "Dynamics of Structures", Prentice-Hall, Inc., ISBN: 0-13-855214-2

FEMA, (2016), "Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook, Third Edition, FEMA P-156", Federal Emergency Management Agency, Washington D.C.

FEMA, (2017), "Hazus® Estimated Annualized Earthquake Losses for the United States, FEMA P-366", Federal Emergency Management Agency, Washington D.C.

ISO/IEC, (2010), "ISO/IEC 1539-1:2010", International Organization for Standardization, International Electrotechnical Commission, Geneva, Switzerland

Lopez, Ricardo Rafael , (1987), "A numerical model for nonlinear response of R/C frame-wall structures", Ph.D. Thesis, University of Illinois at Urbana-Champaign

Otani, S., (1981), "Hyteresis Models of Reinforced Concreted for Earthquake Response Analysis" Journal of Faculty of Engineering, University of Tokyo

Sennett, Robert E. , (1994), "Matrix Analysis of Structures", Waveland Press Inc, ISBN: 1-55766-143-5

Wight, James K , MacGregor, James G , (2009), "Reinforced Concrete Mechanics And Design 5th Edition", Pearson Prentice Hall, ISBN: 0-13-228141-4,