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Replacing scale models of engineering structures with the adoption and use of models defined with digital tools

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Abstract – **It is most likely that at the beginning of the 21st century, with the 4th industrial revolution, we will find ourselves at the borderline between technique and technology. The question underlying this article is whether the technological advance that the construction industry presents today can lead to the full replacement of the technique in the testing laboratories. Decisions on structural systems extracted from these laboratory-made physical models were often accurate, but the cost and time involved made the validation method low-yield. Today, through digitalization, all structural concepts can be directly realized in 3D with software specially designed for the AEC (Architecture, Engineering & Construction) industry. Models made in this way can be developed down to the smallest detail, can be calculated and dimensioned from a structural point of view under different assumptions, and then can be georeferenced and managed from the point of view of assets.**

Keywords: digitalization, FEM models, silos, scale models, numerical models.

1. HOW HAS DIGITIZATION REVOLUTIONIZED THE AEC INDUSTRY?

The evolution of AEC worldwide has been and continues to be influenced by three major components: the climatic component, the geopolitical component, and the economic component. By direct and detached comparison with other industries, the construction sector is very difficult to predict, having a particular dynamic.

Today, based on documented studies for this article, if we are to evaluate the Architecture Engineering and Construction (A.E.C.) field, we are talking about a market whose size was valued at USD 8.9 billion in 2022. The digital wave and the acceleration of the process of implementing technological means are causing this sector to have an estimated growth of up to USD 16.5 billion by 2030.

These values are a very good indicator of the volume of investments that will take place in the coming years in the two fundamental components: new investment objectives (proposed constructions) and the rehabilitation of the existing built environment (existing constructions). Indeed, we are also talking about existing constructions in the era of digitization, as they generate both the necessity and the opportunity for investments in the area of improving energy performance and reducing the carbon footprint.

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Both the means, the tools, and the market itself are regulated by specific legislation. This is a known aspect, but the new generation of construction standards (structural Eurocodes, NZEB, urban planning legislation, etc.) will introduce BIM (Building Information Modeling) and IoT (Internet of Things) valences

The growth of urbanization and industrialization, the increase in living standards, the rising demands for quality of life, the economic growth, and the prevalence of advanced technologies have led to a rise in construction activities over the past few decades. Thus, the expansion of the real estate sector and the growing initiatives towards the construction of smart cities, with zero or near-zero energy consumption, are favoring market growth, opening strong directions towards the development and management of databases.

Digitization through the adoption of BIM standards will regulate the principle of data federalization, meaning it will regulate the data flow during the investment process as well as post-investment between the designer, beneficiary, property/facility managers, and the construction's informational model.

These main drivers of market development are also identified in Romania, with digitization now playing a defining role, increasingly supported by various funding programs. All these digitalization-related funding initiatives in construction are encouraged to achieve both the efficiency of the design-execution-operation process and to meet the demands imposed by environmental protection standards (e.g., reducing energy consumption, reducing carbon emissions, etc.).

In the 1980s and 1990s, the main tools used for risk assessment in construction projects were deterministic mathematical analyses and statistical analyses carried out by specialized state institutes. Due to the computational technology not being sufficiently developed for specific construction industry applications, it was not used as a tool for identifying, calculating, and sizing risks.

With the accelerated development of ICT (Information and Communications Technology), software components began to be increasingly used by specialists as a means for managing risk factors and for decision-making before or during the implementation of investments. Given the current dynamics of the sector and the rapid pace of technology implementation and use in construction design and execution, we must at least, in principle, be able to talk about better risk rationalization and the streamlining of flows between processes marked in the investment schedule.

Each investment, whether it involves the rehabilitation, restoration, or consolidation of an existing building or the construction of a new one, is based on the fundamental principle of engineering, which is the need to ensure a rational balance between the cost of achieving the investment objective and the operating costs of that objective.

The fundamental principle of engineering, or more broadly, of technical sciences described earlier remains unaltered. However, the means by which adherence to this principle is ensured are evolving exponentially, both in number and quality, year by year.

2. TECHNIQUE VS TECHNOLOGY

2.1. Scale models vs digital models

Analyzing the evolution of regulations and standards worldwide over the past 20 years in the field of principles for evaluating structural systems, it can be stated that increasingly less validation is recommended to be done on scale models in testing laboratories, and increasingly more validation of results is recommended to be done based on digital modeling or finite element modeling. These latter two modeling techniques can capture more aspects related to behavior by considering geometric or material imperfections than models built in laboratories for simulations.

Advanced modeling with specialized finite element analysis software is much faster and can capture the physical phenomenon in a significantly shorter time and at much lower costs compared to a model developed in a laboratory. The advantage of finite element modeling, especially in the case of special structures (silos, tanks, pipelines, galleries, etc.), is the precision of generating results – the results are extracted directly at real scale, thus avoiding human error in interpreting the behavior of a structure or structural element analyzed on a scale model in the laboratory.

With the help of calculation programs, boundary conditions for the continuous analysis environment can be imposed, constraints regarding the behavior of elements based on strength criteria, as well as stability behavior, can be imposed. Additionally, all these constraints – being part of the data matrix – can be varied combinatorically, resulting in a qualitative number of iterations that will subsequently lead to the best techno-economic decision regarding the analyzed system.

Besides all these advantages brought using advanced numerical models, there is also a major disadvantage related to the level of preparedness of the structural design engineer who owns the model. In the current dynamic of design activity, the structural design engineer who works with such calculation models must necessarily have knowledge and competencies in BIM modeling, in addition to all other practical and theoretical competencies.

From the few elements presented in this chapter, both the design activity and, to a certain extent, the execution activity – as is normal – involve a migration from technique to technology; increasingly, more construction solutions are adopted based on software evaluations and measurements rather than laboratory or on-site testing. However, even in this era of technological supremacy, there is a field of construction where technique remains predominant: geotechnical engineering. In geotechnical engineering, although there are regulatory norms for including 3D stratigraphic models in the content of geotechnical studies and projects, many prospecting and geotechnical parameters are extracted and validated from laboratory tests and site instrumentation.

Probably, once these 3D models become data stored on centralized platforms and managed by the Territorial Administrative Units of the State, they can be accessed online directly by the investment beneficiaries, eliminating the necessity for technical resources to evaluate soils and their behavior for certain project phases or investments.

3. ARE NUMERICAL MODELS DIGITAL MODELS?

Digitization, being one of the main drivers of growth in the construction industry both internationally and in Romania, has led to a transformation in how constructions are designed. Compared to the end of the 20th century and even the first decade of the 21st century, the quantitative and especially qualitative level in the development, delivery, and execution monitoring of a project has grown exponentially. Today, we speak of constructions with spectacular architectural morphologies that impose specific requirements, thus presenting structural design engineers with challenges in choosing the appropriate structural systems.

Another pressure on structural designers comes from the types of construction materials used in future projects, as well as the nominal geometries of the elements that make up the load-bearing structures – these dimensions are requested to be as small as possible, a condition imposed by architectural rigor or, most often, by the client.

In current design activities, it is becoming increasingly difficult to verify and size structural elements without the use of specialized numerical calculation software. Manual (direct) calculation is most often used for simple checks specific to the behavior of an isolated structural element.

Starting from the premises of this chapter, advanced numerical modeling is recommended by the new national standards and the rules and principles of the Structural Eurocodes, as this is the only way to capture with much greater precision the effects brought by design loads on structural elements.

The value of the data contained in the matrix of such a finite element numerical model, even if the analyzed structure is not extremely complex and does not have a high number of constituent elements, is important because it can serve as a starting point for all other specializations that are integral parts of the project. Calculation programs have reached a level of maturity today where they can detail a load-bearing structure to the extent of 3D modeling programs with Building Information Modeling (BIM) capabilities, even allowing the export of all information directly into collaborative data platforms.

We present this description not because it cannot be easily observed in the current design activities of buildings and engineering structures across all industries, but because today, advanced numerical models created with finite element programs are powerful sizing tools. At the same time, they are complete digital models that can be used for making decisions about the overall investment.

4. EVALUATION AND VALIDATION OF STRUCTURAL SYSTEMS THROUGH ADVANCED NUMERICAL MODELING

In the first chapter of the article, we described the fundamental principle of engineering from a techno-economic perspective, specifically regarding the efficiency of an investment. Now, if we focus strictly on the technical and theoretical aspects of engineering phenomena as they apply to the durability and safety of constructions, we can assert that the fundamental principle of engineering is to identify optimal structural systems that are safe against hazards of any kind for various engineering structures.

The authors' experience in designing special constructions will lead to the presentation of examples detailing the evaluation and validation of specific structural systems, particularly those of metal silos. This type of structure has always been associated with advanced phenomena in the behavior of structural elements, especially in the realm of failure due to the loss of local or general stability of the membranes that make up the walls.

After reading and understanding the design principles described in the Structural Eurocodes regarding these types of constructions, it can be deduced that three types of calculation models are recommended for the evaluation and validation of actions (loading hypotheses) and effects (resistances): manual calculation model, semi-automatic calculation model (manual and numerical analytic), and advanced numerical model (fully automatic model), most often implemented using the finite element method.

Manual calculation methods for evaluating the buckling of steel plates have been successful for a long time, often establishing themselves as the standard. Thus, starting from the conceptual framework used, these methods form both the basis for validating numerical evaluations, being directly adopted in the design process, and provide the foundation for interpretation for each type of evaluation.

The manual calculation process follows a logical sequence of steps and begins with determining key resistances: the plastic limit load and the linear-elastic critical load. These two loads are used to determine the relative slenderness of the plate, which governs the assessment of the relative importance of elastic and plastic behavior. After this assessment, the geometry of the silo, the considered loading hypotheses, and the quality of fabrication lead to a calculated estimation of characteristic imperfections, which are then used to determine the sensitivity of elastic buckling resistance to both imperfections and geometric nonlinearity. The geometry and calculation hypothesis are used to determine the shape that elastic-plastic interaction should take. In the next phase of manual calculation, the elements are then combined to determine the characteristic resistance to elasto-plastic buckling.

Finally, the characteristic resistance is increased by a partial factor (safety factor) to obtain the design value of the elasto-plastic buckling resistance. Where numerical analysis is performed, some or all parts of the manual calculation process can be replaced with a more precise evaluation of the numerical results. When a fully nonlinear buckling analysis is performed on a shell (mantle) appropriately modeled with geometric imperfections, the entire manual calculation process, except for the partial safety factors, can be replaced with this numerical calculation model.

The buckling behavior of metal plates is a complex phenomenon that must be classified and evaluated with appropriate material behavior theories. Analyzing this behavior in steel plates is meticulous and requires the use of advanced numerical methods or models because it represents one of the most important causes of failure in silos, tanks, or pipelines. Probably the most crucial calculation stage of all is the classification of the type of buckling or loss of stability. The classification of buckling is mandated by normative prescriptions, specifically by the rules and principles of SR EN 1993-1-6. Regardless of the type of buckling encountered, it can be mathematically evaluated using one of the methods described in the standard. SR EN 1993-1-6 provides a range of alternative calculation methods, with the differences between them depending on the type of analysis chosen for application.

Beyond the numerical methods used to evaluate the buckling behavior of metal plates, several other conditions must be met for proper finite element modeling. These shape conditions and consideration of imperfections are less captured in the numerical methods applied in manual calculations, but they are extremely important in buckling behavior evaluations when complex calculation models are chosen for numerical analysis using FEM programs, and where the interaction between structural elements is considered.

From a geometric perspective, the standard SR EN 1993-1-6 cannot be applied to the calculation of cells with a wall radius-to-thickness ratio outside the range of 20 – 5000. Additionally, the code does not cover materials whose ductility is inadequate, meaning materials for which failure is brittle or have a short plastic yield plateau. According to the design standard, it is mandatory to establish the boundary conditions for the elements included in the calculation model. The boundary conditions must ensure and maintain the circularity of the membranes. Meridional boundary conditions typically assume, unless otherwise specified, the complete transfer of membrane forces from circular plates. If tensile forces are induced at the ends in the boundary condition area, it is assumed that the contact area or support can transfer the stress without any separation.

In a simple comparison with advanced numerical calculation models for silo cells, in manual calculation, the surface of the metal plate is subjected exclusively to distributed loads (compression or tension), and in the boundary condition area, residual linear loads are considered.

In any realistic and comprehensive structural analysis, such as the use of a global behavior analysis, a loading hypothesis includes within it different concentrated loads, linear distributed loads, and various other distributed loads (pressures, temperature variations, or other actions) that can vary from one location to another on the structure. Therefore, it is not possible to provide a single "failure load" as a unique value that can be ultimately called the "resistance of the structure." Thus, the resistance can only be described in terms of the "loading model" applied to the structure. The expected result is that the design actions are used in the analysis, and in the end, the factor by which these actions can be increased before failure occurs is determined. This factor then becomes the dimensionless resistance of the structure for the analyzed group of design actions.

5. ADVANCED NUMERICAL MODELS AS A BASIS FOR SIZING AND VERIFICATION IN THE 2ND GENERATION OF EUROCODES

5.1. Perspectives and recommendations

The computational power of hardware devices today is incomparably higher than what was available in the early 2000s. This significant advancement allows for the widespread adoption of advanced numerical models as the basis for sizing and verifying load-bearing structures, regardless of the material being analyzed. Numerical calculation programs can capture any type of physical-mechanical parameter of the material and any type of behavior or imperfection at the level of calculation sections.

Practically speaking, given the exponential evolution in computational power in this field, the second generation of Structural Eurocodes will propose new methodologies for the analysis and verification of load-bearing structures that will no longer be suitable for manual calculations. Laws, rules, and principles will be described for the conceptual understanding of the analyzed phenomena and the requirements regarding the safety, strength, durability, and performance of buildings.

This revolutionary perspective of the most advanced design codes in the world will guide new generations towards digital modeling, numerical modeling, and a structural engineering profession that will require mastery of the fundamental concepts of composition and sizing of load-bearing systems. This will reduce the burden of learning and applying direct calculation of stress or deformation values.

The strategy of the European Committee for Standardization (CEN) through the implementation of this new generation of Eurocodes is to simplify calculation procedures, not by reducing or diminishing them, but by integrating as much as possible the resources of finite element numerical calculation and digital modeling in a general sense. Thus, all these new regulations reflect the CEN's vision, at least for the next two decades, on innovation trends in the field of structural design, practice, and safety in structural engineering.

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