Integration of BIM and FEA in Automation of Building and Bridge Engineering Design

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Abstract –

Current development in structural engineering allows designers to create efficient and controlled structural systems, which lead into savings in terms of financial cost, time consumption and lack of lucidity in structural designs. Building Information Modeling (BIM) creates a great opportunity for cooperation of individual experts within one project to maximize an efficiency of the design and minimize errors between concrete details of the entire design and management process.

Physical behavior of structures could be currently controlled with high accuracy by applying numerical simulations using Finite Element Analysis (FEA). Full integration of BIM and FEA allows complex monitoring of structural design during the entire development through initial design, manufacturing processes, and construction through thel structures' life-cycle. The presented paper deals with experiences of major bridge and building engineering projects concerning interoperability of BIM and FEA. Future vision of BIM and FEA integration considering current key findings in the visionary model are also presented. Most of BIM software already enable interoperability of BIM and FEA, however certain issues are still not achieved, especially considering extraordinary geometry characteristics of structures. Because of incomplete interoperability of BIM and FEA, engineers apply them separately, which in turn impairs efficiency of the design. Bridge and building engineers play major role in software applicability and development as well as software developers. The errors occurred during a design should be reported to software developers to improve the applicability and minimize errors in the future structural designs.

Keywords –

BIM; FEA; Interoperability; Bridge engineering; Building engineering

1 Introduction

Efforts towards economic and energy efficient designs in construction engineering and other associated professions support the invention and development of new technologies that allow quicker and more efficient design and control of a structure during the entire life-cycle. Building Information Modeling (BIM) represents one of the most important information management systems of construction industry. It allows detailed information about all objects implemented in a project, and also controls their interaction and behavior while they are in use. The aim of the BIM is to connect of teams and experts involved in the project allowing their collaboration and sharing of ideas while minimizing errors caused by e.g. misunderstanding of cooperators and incompatibility of individual objects.

Traditionally, the information is exchanged between project participants through two-dimensional drawings and other paper documents such as cost plans. In this matter, the collaboration is limited and opens space for errors in the design leading to inefficient and unsustainable results and/or unexpected additional costs. The BIM represents digital virtual model where each elements that effects the structural design and/or its life-cycle is described in detail. The BIM is an IT-based information system recently operated by an increasing amount of Architecture, Engineering and Construction (AEC) companies. The process of the design usually consists of architectural design that creates exterior and interior features of the structure, consider renewable energy system (RES) effort and incorporation of energy analysis tools [1]. Then, structural design provides a sustainable design of individual elements and complex structure as a unit with collaboration regarding geological prospects. In the case of residential and non-residential buildings, systematic design is likely included; for instance heating, ventilation and air conditioning (HVAC). Traffic and bridge engineering structures design features of surrounding infrastructural accessibility for vehicles and/or design of roads or rails.

The BIM represents area for specialists, researchers and developers not only in the building engineering and financial resort, but also in an information system (IS) research that can be of significant contribution in current and future BIM development [2]. The collaboration across different applications within BIM requires creation of a multi-disciplinary platform with identified technical features. BIM-server research and development facilitates the collaboration of BIM participants towards intelligent and automated collaboration [3].

One of the most important numerical techniques used by structural designers for physical phenomenon simulation in structures is the Finite Element Analysis (FEA). This method allows designers to simulate the natural behavior of solids, liquids, gases and their interaction. Static and dynamic analysis of common structures, as well as extraordinary structures, can be simulated with high accuracy. The FEA achieves very good results in many professions, such as medicine, mechanical engineering, building and structural engineering, automotive and aeroplane industry but also in gastronomy, etc.

In comparison, the BIM considers every detail of the design including processes in time-schedules. FEA usually simplifies the structural model that leads to saving time and energy. Interoperability of FEA and BIM extends complexity of digitalized designs leading to simulation of structural behavior before, during construction until the end of their life-span.

Integration and interoperability between the BIM and other applications have been studied to promote and develop the BIM, such as BIM and geographic information system GIS [4, 5], architectural design [6, 7], site-linked BIM concept [8], etc.

2 BIM and FEA application

The current market already offers many software applications allowing the cooperation of BIM and FEA. Many companies are experienced in interoperability of BIM and FEA by transferring .DWG and .DXF formats leading to transfer geometrical entities only. The interaction of BIM and FEA is performed via different software that usually causes loss of some information, depending on geometric complexity. This procedure does not usually allow the exchange of material properties and boundary conditions. The importance of full interoperability between BIM and FEA consists in smart data exchange, where certain simplifications are made and the interaction can be performed to both directions. This means that the BIM model transfers digital data into the FEA considering all necessary parts needed for the study and the BIM is updated at the same time as FEA is performed. The process of integration of FEA and BIM can be illustrated as in the Figure 1.

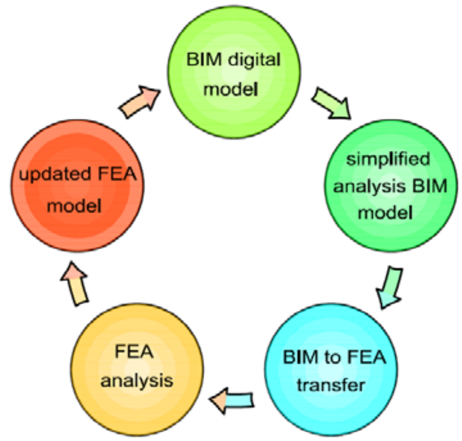

Figure 1. BIM and FEA integration

The current state of the integration of FEA and BIM consists in creating model in BIM, transferring the model to FEA, numerical simulation and evaluation of the obtained results. In the case the results are accepted, the model is not transferred back to the BIM, but the used as such. Otherwise, the model is modified until the goal is achieved and then transferred back to BIM. The difficulties appear especially if detailed and special analysis, such as airflow, thermodynamic, seismic, and other mostly dynamic analyses are needed. The mentioned analyses are usually time consuming and have high requirements for hardware, hence certain simplifications must be used. Structural details, for example bridge equipment, such as handle bars, electrification, lamps, etc. are removed from the FEA model to minimize its size as far as the removed elements don't markedly effect the solution. From this point of view, the FEA should still be considered as individual process requiring detailed professional attention.

In many cases, BIM software allows a certain finite element analyses that can be applied in the BIM directly. On the other hand, FEA specialists prefer specialized multi-physics FEA software where more options of special simulations can be realized. This slows down the BIM process considering difficulties that may occur in transferring the digital model. If the simulation is performed within the BIM software, the integration is usually very good and the probability of occurred errors is minimized. However, extraordinary structures such as bridges, towers, high-rise buildings, etc. quite often represent structures which are significantly affected by dynamic forces, i.e. wind and earthquakes. These kind of analyses are better simulated in multi-physics software in detail, because the correct numerical model definition, solution process and achieving results is likely more accurate and controlled.

The FEA is generally represented by three procedures;

preprocessing, solution and post-processing. The current FEA applications already allow parameterization of the model, which opens space to mathematical techniques that require re-definition in the preprocessor based on results obtained in the post-processing, such as optimization. Hence, the optimization or other loop technique applied in the FEA create their own part of the design. Then, the illustration in the Figure 1 can be updated as follows (Figure 2).

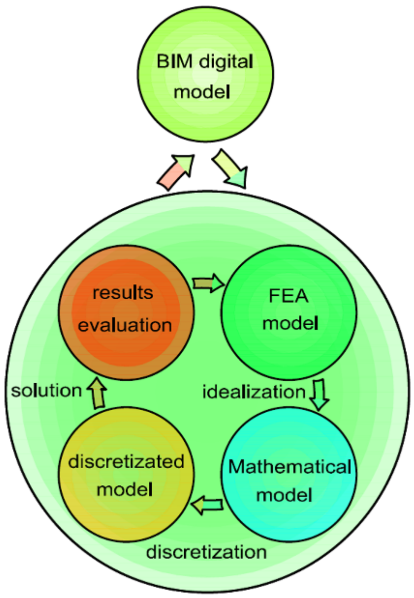

Figure 2. BIM and FEA integration considering loop computing technique

2.1 FEA in bridge and building engineering

The FEA is a numerical technique for finding approximate solutions of partial differential equations as well as of integral equations by variable methods. The method consists in discretization of complex model into small elements. The FEA allows the simulation of a structural behavior close to reality that leads to more accurate and economically efficient designs. The FEA applications have recently applied extensional modulus that allows expanding the structural and mechanical analyses in advanced mathematical techniques supporting efficient designs, for instance optimization. Application of mathematical techniques usually requires a parameterized FEA model. It means the model geometry, loading, material properties and other mechanical and physical features are described in the parameters that represent variables in mathematical expression. This allows the adaptability of the model and its properties to create an optimal design. The FEA represents important part of current designs regardless of the type or characteristics of the structure. The simulation of advanced physical phenomena has been applied in analyses of dynamic behavior of extraordinary structures such as bridges, towers, skyscrapers, wind mills, etc. caused by imposed loading such as wind and seismic activities. The FEA can perform one- to three-dimensional structural problems. Three-dimensional extraordinary structural models represent mathematical challenges that can hardly be performed manually, especially when considering the objects' dynamic behavior. The 3D simulation represents demanding modelling even for the currently available hardware. In many cases, complex models consist of millions of finite elements that represent several equations to be solved, depending on specific features of the analyses (Figure 3).

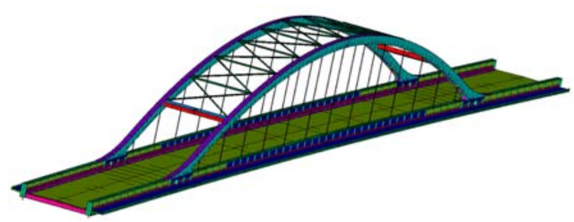

Figure 3. FEA bridge model

Time-dependent analyses may take several hours or days to solve. This may cause issues in the cooperation between interoperable team members and slows down the entire design process. That is why the FEA models are usually simplified to achieve satisfying accuracy of results but without excess time consumption. Currently the FEA is, among others, also applied in "simple" structures such as residential and non-residential building designs to simulate air and heat flow or mass transfer. This allows control beyond energy efficiency of the structures and health conditions indoor and inside the structural elements to ensure health environment of inhabitants and sustainability of the buildings. Advantages of the FEA consists in accuracy and wide-range of usability in many professional fields. As a disadvantage one could consider the strong dependency of errors and need of experience and judgment of a user – the method is still far from the simplicity required to be used by a regular consumer. In the case of contradictions arise during the preprocessing stage, the results and sequential design may cause fatal errors.

2.2 BIM in bridge and building engineering

Standards lead engineers through parts of BIM that have been developed by the BuildingSmart and are continuously updated. Guidelines determining the requirements for BIM in new building designs, renovation and management facility were published in Common BIM Requirements 2012 (COBIM 2012). COBIM 2012 includes, among others, the requirements for architectural design, structural design, energy analysis, management of a BIM project, use of models in facility management, use of models in construction, etc.

BuildingSMART has estimated a usage of BIM in building engineering sector about 20-30% in building projects. It suggests 20% use in public sector, less than 10% in private sector, 40-50% in large construction companies, less than 10% in small construction companies and around 70% among AEC's. The lack of BIM application is specially caused by private companies that have not found its benefits yet. The discouragement is caused by high initial expenses where the adaptation of structural design requires further education of designers, constructors, financials and customers about BIM.

BIM in bridge designs is also widely discussed and studied topic[9]. The most bridge designs still prefer traditional methods [10] although pilot projects of BIM in bridge designs applications have proven the benefits of the 3D visualization and close collaboration of all involved parties.

Next to the continuously developing guides and standards for BIM application in building engineering, a guide applicable to bridges has been recently provided. BIM Guidelines Applicable to Bridges provides instructions on uniform processes for the BIM-based design, implementation and maintenance of bridges [11]. The guideline includes information of how to proceed during the entire process and life-cycle of BIM-based design of bridges. The investigation and possibilities in BIM bridge designs have been performed in development projects, e.g. Älykäs Silta, 5DSilta, 5DSilta2 and 5DSilta3. This research focused on the development of 3D laser scanning GPR scanning of bridges and transferring the measurement and road geometry to the 3D bridge modelling [12, 13].

3 BIM interoperability

The AEC industry still widely uses geometry-model based applications although a building-specific data model has been on the market for more than 20 years [14]. The issue in commercial vendors' applications is using the internal communication technique that doesn't allow direct collaboration with other programs and applications. The proprietary techniques slow down or disable communication between different object-based building data models. Interoperability between project team members and software applications is a key to success in efficient design in any kind of structural engineering projects.

The neutral platform for the object-based building data model is represented by the Industry Foundation Class (IFC) developed and continuously updated by BuildingSmart Alliance. The BuildingSmart Alliance (International Alliance for Interoperability – IAI) is a global consortium of commercial companies and research organizations founded in 1995 [14]. BuildingSmart drives the transformation of the built environment through entire design, processing and maintaining and defines international standards for OpenBIM. The idea of OpenBIM is the interoperability of various BIM applications regardless on developer or producer of the software. The smooth interaction of team-members participating the BIM project is the key in efficient designs. The OpenBIM welcome software vendors, designers, engineers, constructors, building owners and investors as well as construction managers in collaboration and developing the OpenBIM idea. The interoperability should be achieved by applying IFC. The IFC object model is in some cases considered as too complex and that it may cause speed and accuracy problems. Therefore, effort towards processing a full object-based model requires simplification of the model into subsets or novel use of XML [15, 16].

The IFC represents standardized protocol for interoperability defining rules for data description and representation the buildings. It is a language for the text-file representation of models and adjacent facilities including constructs for a wide range of modelling features, such as geometries, management facilities, electrical, mechanical and other subsystems, processing, maintaining and cost models [17].

4 BIM and FEA integration

The successful integration of BIM and FEA consists in proper communication between the applications to control the efficiency of the design and correct data transfer. Special engineering field discussed in a matter of the BIM and FEA interoperability is a bridge design. Bridges are, in most cases, extraordinary structures of unique shapes and features, where a major role play dynamic loading and infrastructural design.

Interaction between BIM and FEA can be performed via direct- or indirect link allowing access to the information needed to analyze the problem and upgrade all changes in the BIM process. The direct link is applied within a software or from one to another via Application Programming Interface (API). An open API is an interface that enables interaction of two software applications to exchange data and communicate. The interoperability of BIM and FEA in commercially available applications has proven successful in both direct and indirect linking of simple structures, but in the case of complex structures the results are yet merely satisfactory. The direct link allows data transfer of geometry, loads, load groups, material properties. Indirect link (IFC) allows geometry and material properties data transfer only. On the other hand, the exterior data transfer through IFC is satisfactory for wide range of designs, as the direct link needs a further development [9]. Also other techniques, such as hybrid method of BIM and FEA application has already been studied in scattering properties of a dielectric targets above a dielectric rough surface [18].

Difficulties in BIM and FEA interoperability in bridge design may occur in the case of complex geometry, where some geometry entities could be of irregular shapes. The accuracy of the FEA depends on a number of created elements. Hence, if the numerical model isn't expressed by suitable amount of finite elements, the obtained results may affect efficient design of the entire structures. Beside the analyses performed within the numerical model representing the real structure, some analyses require also a model of the surrounding space. For instance, analyzing airflow around the structure or its components requires numerical model of the ambient space and the structure is represented by its boundaries only (Figure 4).

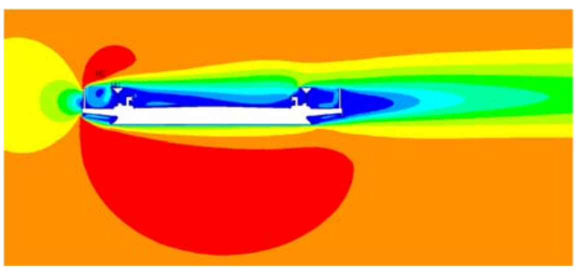

Figure 4. FEA bridge cross-section wind flow

5 Conclusion

Recently, the use of BIM design has increased its popularity. It allows not only 3D visualization of a model but at the same time it provides management information data. Through the BIM, all project participants are connected and share information to achieve more efficient design, manufacturing and construction process and maintenance the structure during entire life-span. The close cooperation minimizes mistakes and errors in the design since any change in the design can be updated by cooperative disciplines.

The idealized full interaction of BIM and FEA saves time and increases efficiency, considering a model is created once in the BIM and linked to the FEA application while any change in the FEA is reflected at the same time back to the BIM model. Although many applications already allow both BIM and FEA, where the data transfer is fully integrated via direct link, the cooperation of project parties is limited by the software they use. The interoperability with no regard to software and applications used can be achieved by IFC that represents open standardized data protocol creating a comprehensive representation of building model [17]. Generally, the interoperability of BIM and FEA cooperates sufficiently up to a certain level. Yet, the further development must be provided in this area.

AEC industry has been developing the BIM continuously to improve the interoperability of all involved disciplines in design, however full integration of FEA has not been developed in detail yet. Construction companies have usually sufficient knowledge about BIM and high proficiency in FEA analyses, but the integrated design knowledge is very limited.

A major progress has been achieved in bridge engineering BIM application as BIM Guidelines Applicable to Bridges has been currently published by Finnish Transport Agency. The guideline defines instructions covering the design phase and content of the modelling [11].

6 Future vision

The aim of the BIM is to create complex control beyond a structural design and management. The complexity consists in digital storage of all data effecting the structural design, structure and management facility throughout the entire life-cycle. Full interoperability of the entire spectrum of involved parties would improve economic conditions, efficiency of the structure and its maintaining to ensure environmental and structural health and extend life-cycle of the construction. Complex BIM design in building and bridge engineering allows controlling behavior of the structure and protect unexpected physical issues before an extended damage. The proper interoperability between BIM and FEA increases the ability to control the structural behavior at its initiation and predict future errors or damage. The importance consists in careful selection of structural elements applied in the FEA.

Essential part of a successful future vision is fully developed IFC that allows collaboration between different software at all four levels; file-level, syntax-level, visualization-level and semantic-level [19]. The benefits from the BIM applications have been already considered, especially in many quite large projects. On the other hand, most of the small companies are not prepared for integrated design yet. The promotion of the BIM application in bridge and building engineering can be performed by arranging workshops and education events with software and engineering vendors. The main issue consists in a fear of investing into the education programs and adapting the design processes into a BIM.

The investors and companies should be aware of the future benefits the systems integration can offer.

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