# FEA in Road Engineering Applications?

**F. Fedorik1[a], T. Makkonen2[a] and R.Heikkilä3[a]**

[a]Structural Engineering and Construction Technology, University of Oulu, Finland
E-mail: Filip.Fedorik@oulu.fi, Tomi.Makkonen@oulu.fi, Rauno.Heikkila@oulu.fi

**Abstract –**

**The current urbanization, industrialization and planning of new city-districts require efficient design to manage the energy, ecology and economical demands set for living environment. The efficiency of Building Information Model (BIM) design in construction sites has been proven through many projects. The full overview and control of design, construction and life-cycle of a structure brings sustainability to buildings and provides optimized purpose for their use. Residential and non-residential buildings, bridges and other civil and structural engineering products will adopt BIM next to benefit from advanced control of infrastructure and related services.**

**Road design is a complex process requiring collaboration in planning, designing, constructing and execution of designs. The design must consider soil investigations, infrastructure planning, various ecologic aspects and the construction designs to achieve the set durability and efficiency goals. This includes the economic implications and planned maintenance during the entire life-cycle of the construction. The impacts of these features could be improved by detailed analysis and monitoring of the physical behavior of the structure during construction and operative use. The physical performance of the structure may be efficiently analyzed by using numerical modelling, such as Finite Element Analysis (FEA). Integration of FEA in the BIM of road design may significantly improve the road construction and its features during the entire life-cycle.**

**The presented paper discusses the possibilities to improve the road designs via applying FEA tools in information model data exchange. The actual on-site monitoring and analysis would improve the quality of the road building and support its efficient and timely maintenance. Active and detailed collaboration of architects, engineers, constructors and facility managers could yield to efficient and sustainable designs and significantly improve the quality of current and future plans.**

**Keywords –**

**BIM; Road engineering; FEA; Interoperability; Efficiency**

## 1 Introduction

The current effort towards developing sustainable, low-energy, financially competent and environmentally friendly objects in civil engineering places designers into position where numerous constraints lead to often sub-optimal design and functionality. Roads used for transportation are one of the most used parts of shared infrastructure and essential part of our everyday life.

Road design is a complex planning process with traffic flow, environmental, health factors and the actual structural design to achieve the performance and safety required. The efficiency doesn't come solely from structural design and planning but also from proper maintenance and sustainability [1] criteria that have to be met during the service time. Along with the cost, climate and physical constraints considered in road and infrastructural design there are also several ecological demands, such as consideration of animal migration dynamics [2].

Among the available processes applied in road and traffic design to achieve a certain efficiency is the BIM (Building Information Management/Modelling). The BIM is mainly used in the large residential and industrial buildings but currently applications extend in other construction areas such as infrastructure. It allows connecting and controlling all involved parties in the structural design, construction and maintenance until end of the structural life-span [3]. The BIM improves efficiency of AECOO (Architecture, Engineering, Construction, Owner and Operator) industry around the world and its application base is rapidly growing [4].

In BIM, the physical and functional features are defined in a digital form continuously updated during the entire life-cycle of the facility. It is a dynamic digital model including all objects affecting the structure and their detailed characteristics, such as dimension, location, material properties, and so on. Besides the BIM as visualization aid and archive of components, there has been also developed techniques allowing performance and quality assessment of such methodologies, such as the Success Level Assessment Model for BIM Projects (SLAM BIM) [5].

An essential part of the road and infrastructure design are safety issues. Although the annual statistics show a decreasing amount of accidents in comparison to increasing trend of traffic participants, the annual number of accidents remain fairly constant [6]. Creating efficient design of a structure usually requires numerical techniques that allow simulating the reality under defined constraints. With such tools, environmental positioning, wear, load bearing, etc. can be assessed beforehand and different designs compared. One of the most common techniques in numerical computation is the Finite Element Analysis/Method (FEA/FEM). The FEA currently represents the most applied methodology for numerical simulation of multi-physical applications. The development in computing performance and the hardware system adaptability allows simulation of complex problems from professions such as medicine, aircraft industry, vehicle industry, gastronomy, civil and mechanical engineering, and so on.

The road design is a complex task of considering the entire spectrum of elements affecting the actual design and functioning of the structure during its life-cycle. By integrating the FEA based tools into the BIM road design, the sustainability of the structure can be significantly improved and continuous monitoring offers a vast set of data important for continuous development of future road and other infrastructure.

# 2 FEA in infrastructure engineering

The Finite Element Analysis/Method is a numerical technique developed for multi-physical phenomena simulation. Together with a rapid development of numerical simulation tools and software the increased complexity of technical and design problems have achieved very high accuracy and convergence performance that supports the creation of more efficient designs with superior number of details.

The road engineering is a common example of a seemingly simple design that actually includes many complex objects that require the attention of competent specialists. For instance, integral part of roads and infrastructural designs are foundations, bridges, viaducts, tunnels, and so on. The FEA became significant part in bridge engineering, considering the effort of minimizing structural costs and creating extraordinary structures characterized by slim elements where dynamic behavior plays significant role in the design and structural use. Before the FEA, most designs relied on performing mechanic calculus and simulation was based on miniatures with limited capacity for detail.

The dynamic forces applied on infrastructural objects from the traffic or the surrounding impact, such as wind and climate effect, seismic activities and other geomechanical processes affecting to the behavior and structural use during the entire life-span can now be included to the design analysis by advanced numerical multi-physical simulations. Alone, they provide the analytical solutions that often remain economically inefficient by accuracy and in terms of construction time due to decoupling of project management and the seemingly independent, often loosely connected, work phases by multiple operators.

## 2.1 FEA in bridge engineering

The FEA represents one of the most important element in bridge design. Extraordinary bridges and the effort of creating unique architectural designs require detailed analyses of structural behavior where analytical solutions are almost impossible or able to provide results only after significant design simplifications that cause inaccuracies in the results.

As the bridges are in many cases characteristic by their slim elements, such as cable-stayed, suspension and pre-stressed elements and structures reinforced by high-strength materials, the dynamic effect represents the major role for stability and comfort of users as well as sustainability of the bridge.

## 2.2 FEA in tunnel engineering

FEA based tools currently allow detail modeling of real structures and their surrounding environment. Although the general public expects three-dimensional complex models, in many cases it requires too much effort and computer time that it becomes inefficient, and often obsolete for the engineers. The choice between 2- and 3-dimensional analyses depends on project geometry and behavior of physical phenomena effecting the problem. However 3D modeling is already possible and it may offer more accurate results and realistic behavior of analyzed physical phenomenon.

Tunnels represent structures that shorten the distance between two points by crossing obstacles such as hills, mountains or waterways. Numerical geomechanic applications have significantly developed in the past decades but still the design is usually demanding task as in the most cases tunnels are of curved cross-section. It means, that evaluation of the cross-sectional forces from the ambient load must be specified in details to the building design of a tunnel to assure its safety.

The tunnel structures must also resist the environmental conditions, such as ground movement and weight and/or water around them. The FEA significantly improves tunnel designs and creates simulation processes where the soil movements can be simulated with good agreement with the actual behavior.

For instance, the analyze performed by Mazek and Almannaei [7] show the efficiency of 2-dimensional numerical simulation in a metro tunnel design. The 2-dimensional FEA simulation allows more detailed analyses in stress, non-linear behavior of the soil and the construction process. On the other hand, in some cases the 3-dimensions are required, considering the surrounding conditions of the tunnel design. The extensive 3-dimensional FEA model of tunnel considering interaction of tunnel, soil and building during excavation process was studied by Keshuan and Lieyun [8]. The interaction of surrounded building significantly affect the soil surface settlement profile. Therefore, depending on geometrical characteristics and surrounding conditions the 2- or 3-dimensional numerical model is required. The efficiency of FEA in tunnel engineering applications and well situated simplifications in the modeling were also performed by Roatesi [9], where good agreement between the numerical and the analytical approach was obtained.

### 2.3 FEA in road designs

The current approach leads road engineers to develop structural material, designs and testing techniques to achieve efficient and sustainable ways for people to move whether the approach and appearance of the ready walkway or highway is novel or historic. In terms of road engineering, mainly soil analyzes and sustainable foundation for infrastructural elements is considered along with sufficiently durable road pavement to last long but allowing fast and efficient replacement after the end of its life-cycle.

A study in which a non-linear FEA is applied in a layered pavement system was performed by Taylor already in 1971 [10]. Unlike at that time, the current computing tools allow simulation of detailed non-linear analyses describing the real conditions although in many cases certain simplifications must be done to streamline the numerical procedure. Except the structural and dynamical analysis of the structural part of the construction, the FEA could be applied for instance in traffic flow by using the fluid mechanics as it was studied by Ma and Cui [11].

## 3 BIM and FEA interoperability

The interoperability of FEA and BIM has been significantly improved in the last decade. Yet, there are still several challenges that should be discussed and tested such as interoperability of different software, geometrical discrepancies and ability of numerical simplifications leading to the efficient simulations as highlighted in [12,13]. The full integration of numerical tools based on FEA in BIM would allow efficient design predicting the real structural behavior by considering realistic boundary conditions. Essential part is also to consider the interoperability between computing tool and on-site measured data that would significantly improve the accuracy of performed numerical simulation. Then, the calibrated numerical model can be further used for forecast and prediction of required maintenance.

Few available software already allow the full interoperability of the BIM and FEA based numerical techniques as they are included in one package. Difficulties occur in cases when specialized parties apply different software that are unable to communicate with each other. Solution for the full integration of specific disciplines in the BIM offers IFC (Industry Foundation Classes) labels that determine standardized data protocols for model representation [14]. The current issue in BIM and FEA interoperability consists mainly in dynamic analyses that require special caution. These are related especially to the objects creating essential part of the road design, such as bridges and tunnels.

The FEA model intended for dynamic analyses is characterized by efficient creation of the geometry to optimize mesh configuration, representing the finite elements and finally leading to accurate results in sufficient time. Hence, the FEA model is usually adapted to specific needs and/or simplified by removing non-critical objects that do not affect the performed analyses but complicate the model convergence.

The critical decision is made in defining objects included in the model transfer from BIM to the FEA tool. In the case, the transferred objects are not correctly connected or there are other discrepancies causing errors in the model, the results obtained in the simulation may be misleading or the simulation fails entirely. This is why proper connection between BIM and FEA should be of special interest as the detailed FEA analyses can significantly improve the design. An example of a bridge illustrated from the BIM road design is figured in the Figure 1.

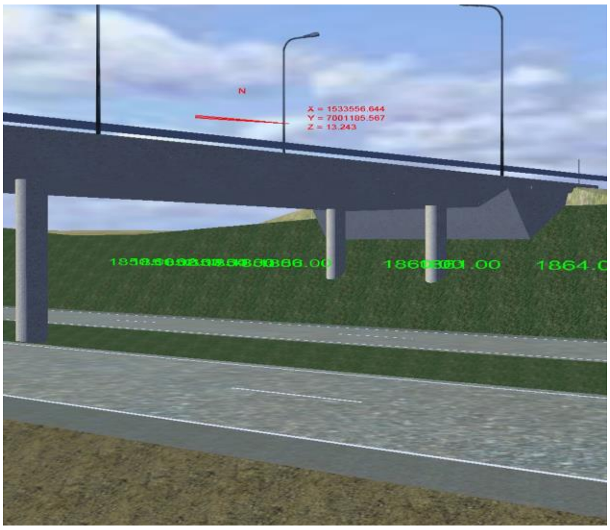


Figure 1. 3-dimensional expression of bridge in BIM design.

## 4 InfraBIM in road engineering

Most of the currently built buildings are designed in a traditional way as 2-dimensional drawings. Although BIM has proven its advantages in many previous projects in number of civil and structural engineering areas, the BIM is mostly used in large projects represented by industrial or residential building of national or international significance. The private sector avoids changes in their current designs as the adaptation towards novel technologies requires patience and certain initial capital costs for educating all involved parties in the project tools.

The current technology development allows advanced road design and maintenance to simplify and improve the construction management from its initiation, and use until the end of the structures decommission and demolition. However, the BIM application has increased a lot in new road designs, but much less attention has been paid in development of maintenance and rehabilitation processes.

The process of road maintenance has been studied and developed within Infra FINBIM research package in Finland since 2010 [15]. The Finnish BIM requirements were released in 2015 by the BuildingSMART Finland within IM3 (Inframodel 3) data exchange format. The requirements cover 11 topics from BIM-based project to utilization of InfraBIM. It is currently required by the Finnish Transport Agency, that the IM3 is used in all designs and implementation projects. An example of 3-dimensional BIM road model is illustrated in the Figure 2.

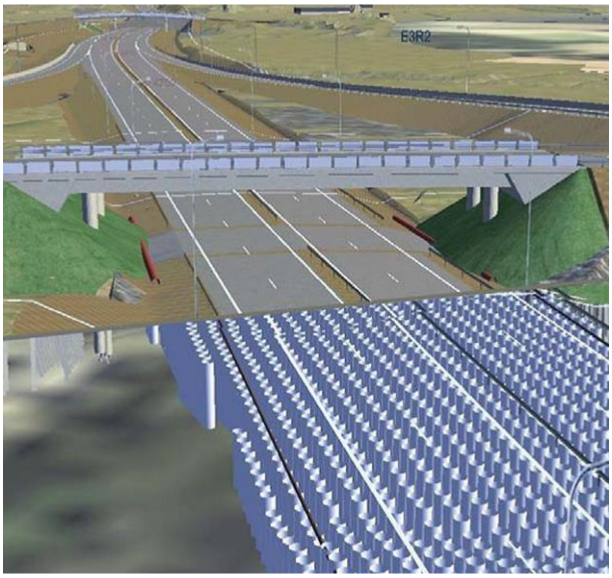


Figure 2. BIM model of road design.

One example of the benefits caused by initiation of national requirements was a large research and development scheme of BIM application in road engineering, performed within strategic program RYM PRE Infra FINBIM in Finland [15]. The goal of the performed project was the utilization of a mobile laser scanning method to obtain the initial data for model generation, testing and development of novel 3D analysis and modeling methods for point cloud processing, applying optimization method for the planning of geometric and structural improvements needed for the existing uneven road surfaces and creation 3D machine control models using machine control systems for continuous control of practical construction work using a milling machine and an asphalt paver.

Extensive research in application the BIM in roads and infrastructure objects have been performed also elsewhere, for instance by Tibaut et al. [16]. The research focused on developing smart parametric building blocks for 3D road design and developing algorithms detecting road elements from the 3D point clouds achieved by a laser scanning.

Great benefits in road engineering can also be achieved by implementing geotechnical data into the BIM process as in most of the projects the below-ground data is not considered while it has marked impact on e.g. foundations and water drainage. Testing different geotechnical data formats and their implementation into the BIM process was studied by Tawelian and Mickovski [17].

The complex BIM process including geotechnical data, bridge, tunnels, road construction and other relevant fields of expertise can significantly improve the entire building process. The quality of the BIM design depends on the quality and the accuracy of initial data and decent collaboration of all involved parties. If data obtained from any of the involved parties is inaccurate, it deteriorate the entire process. This holds especially with the geotechnical investigations, as if the data of below-ground material is incorrect the actual design may face risks that affect the road usability, safety, durability and sustainability.

Besides the road construction itself, another essential part is the infrastructure planning stage that is currently also developing affected by environmental degradation, climate change and social trends [18].

## 5 BIM, FEA and road design interoperability

The vision of the future civil and structural engineering design is in complete breakdown of the initial design and its full-scale control over the entire life-time until the stages of deconstruction and recycling the material. The current design does not usually combine detailed structural analysis and digital system represented by BIM. This is caused by difficulties occurred within transferring the digital data from BIM structural design into a numerical tool. There are few reasons for the difficulties that occur in different coding phases within the applied software and/or difficulties in accurate definition of numerical model.

The numerical modeling is a separate field of expertise where the numerical model requires elements essential for performed analyses. On the contrary, the BIM model includes the entire spectrum of objects affecting any stage of the planning and life-cycle of the structure. The goal of the BIM in the future is complex planning and control of the structure including all parties without consideration of what computing, design and facility tool is applied. From this reason, a global standard is proposed for unifying the BIM parts has been developing through IFC. It would allow the connection of all involved disciplines and minimize any misunderstanding and contradiction in the planning and design stages.

The BIM is a well-known and widely applied method in road engineering. The current technology allows automatized processes in structural and traffic construction engineering significantly improve the infrastructure design and maintenance. The development in the use of BIM and 3D machine control in new road designs has high significance in Finland as well as in other Nordic countries. For instance, studying and development of road maintenance processes has been active since 2010 within the Infra FINBIM research [15].

Interoperability of BIM and specialized areas require full integration and complete understanding to avoid any errors uprising from the data transfer. There has been significant development in this matter, however there are still challenges that must be solved. The interoperability between Geographic Information System (GIS) and BIM was performed by developing by combination of IFC and CityGML as both data information platforms can benefit from each other (Geography Markup Language) [19,20].

## 6 Conclusion

Since 1970s there has been significant progress in BIM application in road designs and infrastructural planning, in parts thanks to increased computing power and easy to use software tools. The goal of fully controlled and integrated design, construction, maintenance and deconstruction during the structure’s life-cycle is today a rapidly developing field. Integration of the specialized BIM digital packages can improve the efficiency and sustainability of the private and public structural projects but the full interoperability remains incomplete to be of use in most projects. The BIM's advantages are already well-known in grand building projects but the small-scale designs are rather conservative in applying novel tools. The future vision consists in the full BIM model allowing the complex control beyond road design and optimizes the maintenance process during the entire life-span of the structure including all the objects connected. Automatized machine control systems, detailed on-site monitoring and numerical computation control can markedly improve the novel design as well as prolong usability of the current ones.

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