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Theory and Applications of Virtual Testing Environments in Civil Engineering

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Physical laboratory-based experiments and tests have been established as a fundamental learning, research and development tool in many areas of Civil Engineering education, science and practice. However, new areas of research in engineering analysis have come about as a result of the changing roles of computational models and laboratory-based experiments. This new environment of engineering is forcing scientists to allocate experimental infrastructures and resources differently. In this respect, Virtual Testing is rapidly emerging as a key technology in Civil Engineering. This paper discusses theory and applications of Virtual Testing in Civil Engineering with a special emphasize on the ICT aspects of Virtual Testing Environments. Furthermore, two ongoing research projects related to the development of Virtual Testing Environments for composite materials and components at Delft University of Technology will be discussed.

Keywords: civil engineering, composite materials, virtual testing, ICT, cases

1 Introduction

Physical laboratory-based experiments and tests have been established as a fundamental learning, research and development tool in many areas of (Civil) Engineering education, science and practice. In the context of education, they have particularly enriched engineering education by helping students to understand fundamental principles by connecting theory and equations in their text books to real world applications with real equipment and data. In the context of science, physical experiments have been used to gain insight into a particular phenomenon in a real-life setting or to verify or validate scientific computational models for a long time. In both educational and research context, this type of physical experiments is generally governed by the available infrastructure and resources at the educational and research institutes, frequently limiting the exposure of valuable materials to a relatively small audience (i.e. high costs versus relatively low benefits).[1]

1 **Kuester, F**. and **Hutchinson, T.** (2007). A virtualized laboratory for earthquake engineering education, ASEE Journal of Engineering Education, 15:1

In the context of practice, physical tests are often performed to validate performances of products. With the increasing regulations from national governments and European Union (EU) concerning quality, safety and environmental properties of products, the number physical tests performed in laboratories of certificated (research) institutes have increased recently. For example, the European labels of conformity, known as CE markings, are a guarantee of quality and safety for products produced and sold in the EU. According to the CE conformity standards, products will have undergone a series of performance tests before they can be sold on the EU market. However, these performance tests entail additional costs which may result in financial difficulties stemming from these additional costs and in the long run result in competitive disadvantages for Small and Medium Enterprises (SMEs) in Europe.[2]

New areas of research in engineering analysis have come about as a result of the changing roles of computational models and laboratory-based experiments. This new environment of engineering is forcing scientists to allocate experimental infrastructures and resources differently. Rather than trying to prove whether a calculation or computational simulation is correct, the focus is on learning how to use experimental data to 'improve' the accuracy of (existing) computational models. This process of improving the accuracy of calculations and computer models is often using advanced statistical techniques of assessing the accuracy of a computational prediction with respect to experimental measurements. In fact, it takes into account that both computer simulation and experimental data have uncertainties associated with them.[3] Thus providing a new engineering environment based on highly-validated computer models and associated experimental data that is able to make highly precise predictions of the outcome of physical laboratory-based tests without the need to perform them in a real laboratory (i.e. capturing the essential characteristics of a physical test). With the application of emerging Information and Communication Technologies, including, Grid Computing, Web Services, Product Data Technology, Semantic Web and Soft Computing, we are able to create so-called Virtual Testing Environments that allow students, researchers and practioners to conduct virtual tests anytime and anyplace. In the next section a short overview of the current applications of Virtual Testing in Civil Engineering is given.

2 Virtual Testing in Civil Engineering

Virtual Testing is rapidly emerging as a key technology in Civil Engineering. Although some applications of Virtual Testing other than related to materials and components have been reported by a number of researchers, most effort has been put into the development of Virtual Testing Environments for composite materials and components.[4 to 8] In this respect, Virtual Testing is mostly defined as a concept of making use of high performance computers in conjunction with high quality models to predict the properties and/or behaviour of composite materials and components. Consequently, Virtual Testing is often seen as another new terminology for Computer Simulation, which is a wrong assumption. Although it is true that Computer Simulation is an important tool for Virtual Testing, it is only one of key components that constitute a Virtual Testing Environment. This can be explained by the limitation of the existing composite material models. As discussed by Garboczi et al an ideal model of a composite material or structure should be one that starts from the known chemical composition of the composite material.[9] Beginning with the correct proportioning and arrangement of atoms, the modeling effort would build up the needed molecules, then the nanostructure and microstructure, and would eventually predict properties at the macroscale level. Such fundamental and multi-scale material model, however, is still a long way off. Each existing material model has its range of applicability and its own restrictions. In addition, many existing material models are scientific-based models that have fundamental parameters (i.e. based on valid mathematical and physical principles) that are not based on experimental measurements. As discussed earlier, within a Virtual

2 **ECWINS consortium** (2007). The Road to Standardized Window Pro-duction. In: Collective Research Projects for SMEs, Vol. 3, European Union

3 **Doebling, S.** et al (2001). Validation of Transient Structural Dynamics Simulations: An Example, Proceedings Third International Conference on Sensitivity Analysis of Model Output, Spain

4 **Kuester, F**. and **Hutchinson, T.** (2007). ibid

5 **Hallbach, E.** (2007). Development of Simulator for Modelling Robotic Earthmoving Operations, Master thesis, Lulea University of Technology, Finland

6 **Ghaboussi, J.** et al (2002). Real-Time Soil Modelling for machine-Medium Interaction in Virtual Reality, Proceedings of the 8th International Symposium on Numerical Methods in Geomechanics, Italy

7 **Cervenka, J.** and **Branis, P.** (2002). Virtual testing laboratory on the Web, Proceedings of the Fourth European Conference on Product and Process Modelling in the Building and Related Industries, Slovenia

8 **Nagy, Z.** et al (2008). The impact of remote and virtual laboratories in engineering education: A Workshop, Proceedings International conference on innovation, good practice and research in engineering education, United Kingdom

9 **Garboczi, E.** et al (2004). Virtual Testing of Cement and Concrete–USA, Concrete International, 12, United States

Testing Environment computer models interact with experimental data in order to predict the properties and behaviour of composite materials and components. In this context, one can discuss about the question whether a functional Virtual Testing Environment actually increases the need for physical laboratory-based testing or not. Even the most convinced adepts of Computer Simulation consider that physical laboratory-based testing is essential to the success of correlative and predictive Computer Simulation work. Currently, we can only speak of complementary Virtual Testing, mainly for cost reduction and re-analysis purposes and it of prime importance not to confront this important topic to that of the experimental validation work which is at least of equal importance.[10]

One of the most influential pioneers of Virtual Testing in Civil Engineering is the National Institute of Standards and Technologies (NIST) in the United States. In January 2001, a NIST/industry consortium was formed to develop a Virtual Cement and Concrete Testing Laboratory (VCCTL). The main goal of the consortium was to develop a Virtual Testing System, using a suite of integrated computer models for designing and testing cement-based materials in a virtual environment, which can accurately predict durability and service life based on detailed knowledge of starting materials, curing conditions, and environmental factors.[11] In 2001 an early prototype (version 1.0) of the VCCTL became public available and accessible through the Internet. The core of this prototype was formed by the NIST 3D Cement Hydration and Microstructure Development Model (CEMHYD3D). Using the web-based interface of the VCCTL, a can create an initial microstructure containing cement, mine mineral admixtures, and inert fillers following a specific particle size distribution, hydrate the microstructure under a variety of curing conditions and evaluate the properties (e.g. chemical shrinkage, heat release, and temperature rise) of the simulated microstructures for direct comparison to experimental data. As the consortium proceeded, the prediction of rheological properties (viscosity and yield stress) of the fresh materials and elastic properties (elastic modulus, creep, and relaxation) of the hardened materials were incorporated into the VCCTL resulting in the release of version 1.1 (latest) of the VCCTL in 2003.[12 13] Figure 1 shows the

10 Kayvantash, K. (2004). Virtual Testing & Modelling: State-of-the-Art Review, European Vehicle Passive Safety Network 2, EU project, [www.passivesafety.com]
11 Bullard, J. et al (2004). Virtual Cement, Innovations in Portland Cement Manufacturing, USA
12 Bullard, J. (2001). The Virtual Cement and Concrete Testing Laboratory Consortium - Annual Report, NIST, USA
13 Bullard, J. (2002). The Virtual Cement and Concrete Testing Laboratory Consortium - Annual Report 2002, NIST, USA
14 vcctl.cbt.nist.gov

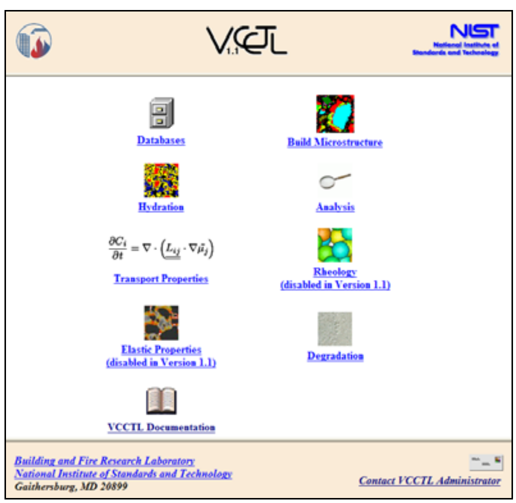

Figure 1 Web-based interface of the VCCTL[14]

In civil engineering, NIST has set the standard for other past and ongoing research and development projects related to Virtual Testing of composite materials and components worldwide. Together with the promises of emerging Information and Communication Technologies a whole new realm of possibilities for developing Virtual Testing Environments has opened. Keywords in this respect are web-based interfaces, interoperability and collaboration. In the next section a short overview of the emerging Information and Communication Technologies (ICT) and their (possible) impact on the development of Virtual Testing Environments is given.

3 Emerging Information and Communication Technologies for Virtual Testing Environments

In order to structure the discussion in this section, a conceptual scheme for a Virtual Testing Environment is presented in Figure 2. A Virtual Testing Environment consists of three main parts (or layers): (1) Virtual Testing Laboratory (system layer), (2) Computer Models (application layer) and (3) Data (data layer) embedded in (1) Hardware Environment and (2) Software Environment.

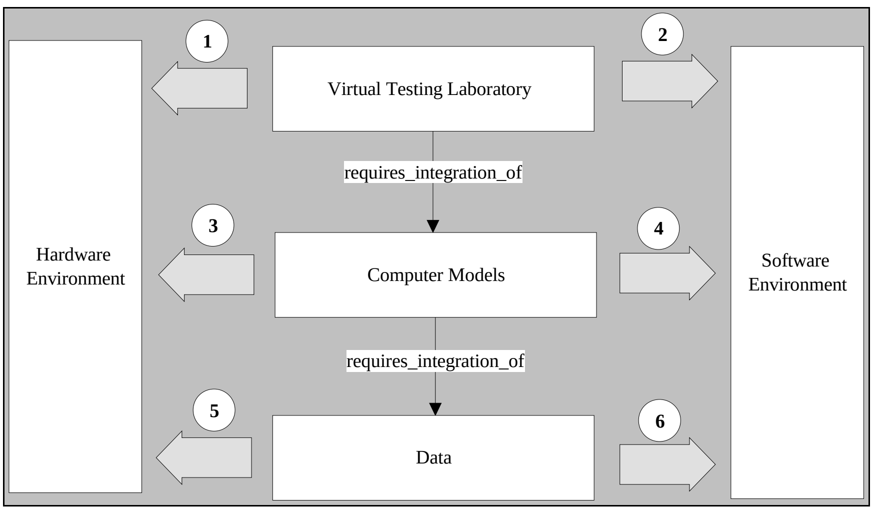

Figure 2 Conceptual scheme for a Virtual Testing Environment

The Hardware Environment, as shown in Figure 2, not only contains computer systems and infrastructure but also can contain (or interfaces with) traditional physical laboratory equipment. In the past, a number of approaches were based on this idea of a Virtual Testing Environment as a virtual web-based interface providing 'virtual access' to physical laboratory equipment and accompanying materials.[15] As discussed by Dado et al, Virtual Testing Environments are no longer regarded as isolated web-based Virtual Testing Environments, but as a set of integrated hardware and software components that, used together, form a distributed and collaborative space for Virtual Testing.[16] Multiple, geographically dispersed (research) institutes use the virtual laboratories to establish their own Virtual Testing Environment to perform experiments and tests as well as share their results. An emerging technology in this respect is Grid

15 Bhargava, P. et al (2006). Web-based virtual torsion laboratory, Journal of Computer Applications in Engineering Eduction, 14:1, United States

16 Dado, E. et al (2005). Exploring Enabling Technologies for a Virtual Knowledge Network for the Building and Construction Industry, Proceedings of the AEC2005 Conference, The Netherlands

Computing technology. At the heart of the Grid Computing technology is the concept of 'virtual enterprise'. A virtual enterprise is a dynamic collection of institutes together in order to share hardware and software resources as they tackle common goals. As an example, consider the prediction of properties of concrete-based structures. Concrete is a composite material which' aspects and corresponding properties need to be predicted on different levels of detail. A multi-scale modeling approach, where these different levels are integrated, leads to a more comprehensive basis for the description of the concrete material performance and increases the accuracy of the prediction of the properties of concrete.[17] However, research in the past has led to the development of specialized computerized numerical simulation models that are developed by and available at different research institutes. A shared access to and the use of these resources is an inevitable condition for making multi-scale modeling successful. Grid Computing technology addresses these needs.

The Software Environment, as shown in Figure 2, is traditionally dominated by (programming) languages such SQL for storing, retrieving and manipulating Data (database), Fortran C, and C++ for implementing Computer Models, HTML for developing web-based interfaces for end-users of the Virtual Testing Laboratory. The Software Environment of the most recent version of the VCCTL (version 1.1), as an example, is still based on these (programming) languages. An emerging technology in this area is Platform technology. Keywords in this respect are Web Services and interoperability.

Web Services fundamentally concern about the interoperability – connecting computer programs to other computer programs, especially when the computer programs concerned are developed using different languages tools and computer platforms. Web Services standards and technologies offer a widely adopted mechanism for making computer programs work together. Currently, the two main players on the Web Services market are Sun, with their J2EE (Java 2 Enterprise Edition) platform[18] and Microsoft with the .NET platform[19], where both agree on the core standards (e.g. SOAP, WSDL, UDDI and XML[20]), but disagree on how to deliver the potential benefits of Web Services to their customers.[21] In the academic world, the J2EE platform has been widely adopted by educators and researchers for developing web-based applications and Web Services. The Virtual Testing Laboratory Service (VTLS) – as an example - provides web-based access to comprehensive simulation tools for the analysis of structural behaviour of civil structures and is integrated as a remote Web Service in the ISTforCE Concurrent Engineering Services Platform (CESP).[22]

Concerning the issue of interoperability we need to distinguish three layers of interoperability: (1) data interoperability, (2) application interoperability and (3) resource interoperability. However, to understand the issue of 'data interoperability', we have to make a clear distinction between the data and information. By definition, data is what is stored in computers or is exchanged by computers. Hence, data is a kind of information (often referred to as syntactic information) that cannot be interpreted by either humans or computers. In this regard, information concerns the 'structured' data that does not need any further interpretation or processing. The common agreement is that the solution of the data interoperability problem is at the information level.[23] This requires technologies and standards that describe information as semantic objects or

17 Koenders, E. et al (2005). A Virtual Testing Lab for Building Materials, Proceedings of the AEC2005 Conference, The Netherlands

18 www.sun.com

19 www.microsoft.com

20 SOAP: Simple Object Access Protocol, WSDL: Web Services Description Language, UDDI: Universal Description Discovery and Integration and XML: eXtensible Markup Language.

21 Dado, E. et al (2005). ibid

22 ISTforCE (Intelligent Services and Tools for Concurrent Engineering) is a European 5th Framework Information Society project (2001-2003) aimed at developing technologies for the next generation of engineering collaboration platforms. istforce.eu-project.info

23 Dado, E. (2002). ICT-enabled communication and co-operation in large-scale on-site construction projects, PhD thesis, Delft University of Technology, The Netherlands entities containing the data it structures. In the last two decades several research and development projects have shown that Product Data Technology provides a good basis for the development of product models which contain the semantic objects and accompanying data. Today, with the development of the Industry Foundation Classes (IFC) by the International Alliance of Interoperability (IAI), the product modeling paradigm has been implemented in many commercial and scientific software.[24] The CESP – for example – integrates internal data models via the IFC 2x product services and makes remote engineering services available.[25] An emerging technology in this area is Semantic Web technology. In the context of data interoperability, the Semantic Web derives its notion of meaning of content specialized vocabularies, referred to as ontologies. In this respect, ontology is a collection of terms used to describe a particular application domain. Build upon RDF and XML and derived from DAML/OIL, OWL has become the default standard for creating web ontologies. Integrating ontologies with Web Services make them visible and accessible for the rest of the world for interfacing with other computer applications (i.e. application integration).[26] Although Grid Computing technology initially was developed as a technique for breaking large problems into small tasks that can be computed independently. With the arrival of Web Services and the Semantic Web, the research community has renewed its interest in Grid Computing technologies. Consequently, a number of research and development projects have been initiated that their main goal is to integrate these different but complementary technologies and thus providing resource interoperability.[27] At time writing, there are no reported cases of semantic web- based implementations of Virtual Testing Environments in Civil Engineering.

Another emerging technology related to the data layer, as shown in figure 2, is Soft Computing technology. As discussed above, one of the most important features of a Virtual Testing Environment is assessing the accuracy of a computational prediction with respect to experimental measurements. In this respect, advanced statistical techniques for data analysis, such as multiple regression and correlation techniques, are often used. Soft Computing technology is a container term which refers to complementary technologies such as Neural Computing, Fuzzy Logic, Evolutionary Computation, Machine Learning and Probabilistic Reasoning. Soft Computing and statistical techniques emphasize different aspects of data analysis. Soft computing - as an engineering science - focuses on obtaining working solutions quickly, accepting approximations and unconventional approaches. Its strength lies in its flexibility to create models that suit the needs arising in applications (e.g. model generation). Statistics – as branch of mathematic – is more rigorous and focuses on establishing objective conclusions based on experimental data by analyzing the possible situations and their likelihood (e.g. model validation). In fact, both technologies are complementary and used together it will enhance robustness and generalizability of data analysis methods.[28] Due to the successful applications of Soft Computing in a number of engineering disciplines (including materials science), Soft Computing is likely to play an important role in future developments of Virtual Testing Environments. Next sections introduce two ongoing research projects related to the development of Virtual Testing Environments for materials at Delft University of Technology.

24 www.iai-international.org

25. Eisfeld, M. et al (2002). Use of ISTforCE Concurrent Engineering Services Platform - A Case Study in Conceptual Structural Design, Proceedings of the 4th European Conference on Product and Process Modelling in the Building and Related Industries, Slovenia

26 Semantic web services applied in the building and construction domain (including civil engineering) is the subject of two ongoing EU FP7 projects, respectively SWOP and INPRO. The main objecttive of SWOP project is Semantic Web-based open engineering platform (SWOP) that will improve complex product development and support actual product customization processes [www.swop-project.eu]. The main objective of InPro is to develop and establish a Semantic Web-based and collaborative way of working in the early design phase, considering the whole life-cycle of a building [www.inpro-project.eu].

27 An example of such a research project is the European IST InteliGrid project. InteliGrid project addressed these challenge by successfully combined and extended state-of-the-art research and technologies in three key areas: (a) semantic interoperability, (b) virtual organizations, and (c) grid technology to provide standards-based collection of ontology based services and grid middleware in support of dynamic virtual organizations as well as grid enabled engineering applications [inteligrid.eu-

project.info]
28 COST consortium (2008). Combining Soft Computing Techniques and Statistical Methods to Improve Data Analysis Solutions, Fact Sheet, European Union
29 Koenders, E. Schlangen, E. and **Dado, E.** (2007). Virtual Testing of Compressive Strength of Concrete, Proceedings of the ISEC-4 Conference, Australia
30 Hymostruc, Hydration model for cement-based materials developed at Delft University of Technology [www.microlab.tu delft.nl]
31 Schlangen, E. (1993). Experimental and Numerical Analysis of Fracture Processes in Concrete, PhD thesis, Delft University of Technology, The Netherlands

4 Virtual Testing Environment for cementitious materials

The section of Material and Environment of the Faculty Civil Engineering at Delft University of Technology has been involved in a number of trials in order to find out the basic principles of which a Virtual Testing Environment should comply with and to find out the conditions at which this Virtual Testing Environment would be attractive to establish.[29] The first trials where focusing on the virtual testing of the concrete compressive strength. In physical-based concrete laboratories, the compressive strength is determined with an experimental device where a concrete cube is positioned in between two steel plates and compressed using a hydraulic force (Figure 3). The force imposed to the concrete cube is increased until failure occurs.

Figure 3 Experimental testing device for concrete compression

When considering a Virtual Testing Environment, this procedure has to be mimicked while using Computer Models. These Computer models are used to simulate the failure behaviour of the material during testing. The input consists of mix design and properties of the mix components used. The simulation of the development of the material properties is conducted with the hydration model Hymostruc and the failure behaviour is simulated with the Lattice model.[30] [31] After mixing of the concrete, hardening commences and the material properties start to develop. This process leads to a set of properties that is unique for every particular type of concrete. Determining the properties of an arbitrary type of concrete in general and the compressive strength in particular, is therefore a necessary need, every time a mix composition alters. Advanced numerical techniques have made it possible to use computer programs for simulating and predicting the material properties, with the input based on the mix composition and cement properties.

The Hymostruc model (Figure 4 left) can be applied to predict the actual state of the material properties in terms of the degree of hydration. The model calculates the hardening process of cement-based materials as a function of the water-cement ratio, the reaction temperature, the chemical cement composition and the particle size distribution of the cement. The model calculates the inter-particle contacts by means of the 'interaction mechanism for the expanding particles' (Figure 4 right) where hydrating particles are embedded in the outer shell of larger hydrating particles. This mechanism provides the basis of the formation of a micro-structure which, on its turn, can be considered as the backbone of the hardening material. When considering the Virtual Testing Environment, the Hymostruc model will be used to calculate the internal microstructure that is necessary to predict the compressive strength of the concrete sample. The microstructure of the material can be considered as the inner structure (paste), i.e. 'glue' that tightens together all the aggregate particles inside a concrete. Collapsing of the material therefore strongly depends on the strength characteristics of this paste.

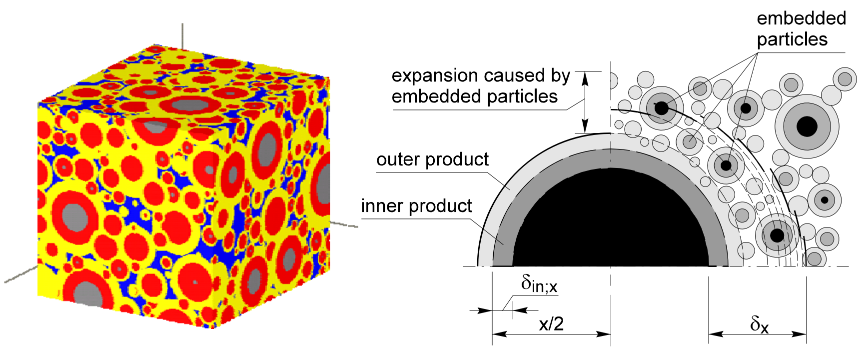

Figure 4 Left, 3D virtual microstructure simulated with Hymostruc. Right, Hymostruc interaction mechanism for expanding particles representing the formation of structure of the virtual microstructure

Modelling the collapsing of the paste in particular and of concrete in general is therefore the logical next step in the development of the Virtual Testing Environment. In order to be able to predict the ultimate capacity of a virtual concrete sample, a fracture mechanics model is required which can handle the crack propagation of the material while loaded. The model adopted in this respect is the Lattice model, which has originally been developed by Schlangen and Van Mier in 1991. The model simulates fracture processes by means of mapping a framework of beams to a materials structure. The basic principles of the Lattice model are schematically shown in Figure 5. In this figure (a) is a schematization of a type of framework that simulates the meso-level structure of brittle materials, like concrete. For concrete in particular, the meso-level structure reflects modelling the paste and aggregates level explicitly. This fits very well with the level that is required for the model that should form the backbone of the compressive stress calculations inside the Virtual Testing Environment. The model should be able to detect failure paths through the material (weakest lings) and to calculate the accompanying ultimate strength of

the building material. Once this failure path has been initiated, the inner structure of the material starts to disintegrate and the strength capacity will be affected.
After having reached the maximum compressive strength, a descending branch will follow that indicates the post-peak behaviour of the material. The Lattice model is capable to calculate this part of the failure trajectory and to quantify this part of the failure behaviour as well. For conventional concretes, the Interfacial Transition Zone (ITZ, weak bonding zone around the aggregates) is almost always the weakest part of the material that initiates and contributes to the failure paths (Figure 4.). For higher quality concretes, the failure paths might cross through the aggregate particles which implicitly affect the brittleness of the material. A proper compressive strength model within a Virtual Testing Environment should therefore implicitly deal with these different kinds of failure mechanisms related to the mix composition in general and the inner structure of the material in particular.

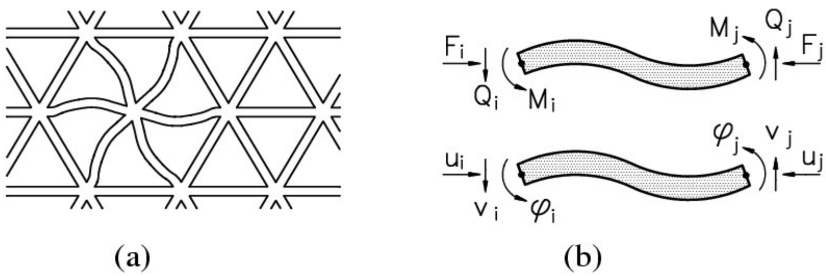

Figure 5 Principle of the Lattice mode

Together, the Hymostruc model and the Lattice model have the potential to be the core of the Virtual Testing Environment's compressive strength model. Therefore, Virtual Testing Environment as foreseen will consist of the following issues:

- an on-line accessible compressive strength model as the first pilot project for the development of a Virtual Testing Environment
- a digital scan of the specimen that should mimic the 'real' test specimen
- a mix composition of a material (concrete), the aggregate properties and the cement properties. The development of the hardening properties are calculated with the Hymostruc model
- a Lattice model framework that calculates the failure traject, the ultimate load capacity and the descending branch of the post-peak load behaviour

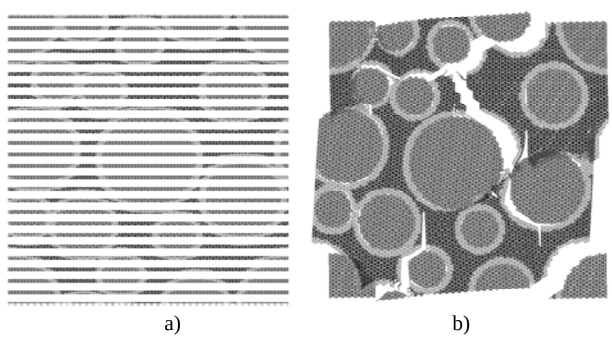

Figure 4 Examples of a concrete specimen modelled with the Lattice model. a) before loading, b) exaggerated deformations after failure of the material. The crack pattern runs through the ITZ (weakest link) and can be observed very well

Within the compressive strength model of the Virtual Testing Environment, the Hymostruc model is used to calculate the internal morphology and strength of the microstructure that is necessary for predicting the compressive strength of the concrete and the Lattice model for simulation of the ultimate capacity of concrete based on a fracture mechanics and necessary to predict the crack propagation of the material during loading. Implementation of the compressing strength model into the Virtual Testing Environment is therefore considered as the first step into the development of a full operating service facility for the Building and Construction Industry. It is expected that the pilot version of the Virtual Testing Environment will provide results that look like the examples given in Figure 5. This figure illuminates the results of a concrete specimen (cubes 15 x 15 x 15 cm3) which were submitted to a compressive force. The specimen was loaded twice until failure and two different failure paths throughout the inner structure of the material were simulated. The left specimen is the result of a real experiment of concrete loaded by a compressive force. The results show vertical cracks which are the result of the mobilisation of horizontal tensile forces, which are mostly initiated by the friction forces that develop between the supports of the specimen and the steel plates of the testing machine. It emphasises the relevance of applying the right boundary conditions for the numerical simulations within the Virtual Testing Environment.

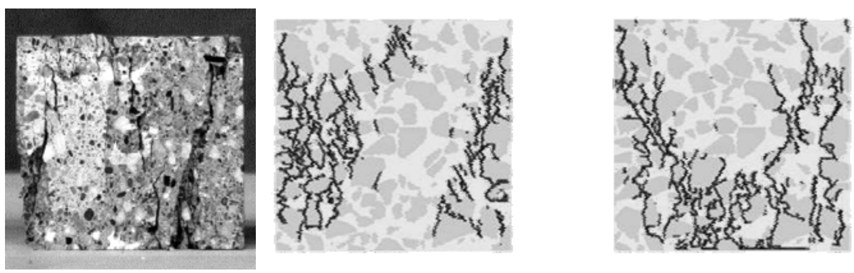

Figure 5 Left: Concrete crack pattern after loading. Right: Lattice simulation

For the middle and right situated specimens, the numerical simulations are presented as calculated with the simulation model Lattice. The agreement between the real experiments and the numerical simulation is quite satisfactory which implicitly indicates the potential of the Lattice model to be applied in the Virtual Testing Environment. The results also show the vertical failure path throughout the specimen and, due to the heterogeneous character of concrete, different failure paths for were simulated as well. The vertical cracks indicate the existence of shear planes through the inner structure. The results show the backbone of the Virtual Testing Environment's compressive strength model and turns out to be very promising.

5 Virtual Testing Environment for CE assessment of windows

As discussed earlier, the requirements of the new CE-conformity standards will make it difficult for SMEs to compete on the EU market. These standards provide a range of compliance routes for products to carry CE mark including independent physical testing and certification of the product through notified bodies. The assessment of performance of a product can be based on mechanical

Surmeli, N. et al (2009). Model-based CE-performance assessment in BC industry. In: Dado, E. Zreik, K. and Beheshti, R. (2009). Innovation for Building and Construction, Europia Productions, Paris, France, pp. 259-276

models based on principles of physical testing (Figure 6).[32] For example, windows manufactures have to physical test the properties of each window type to obtain CE-Conformity. However, it's very difficult for SMEs to provide all the necessary testing for their window types. The formal requirements of the standard can be put in practice easier by industrial manufacturers. Without any support by their Associations, the SMEs will depend more on industrial suppliers. Based on these observations, the 'Fachverband des Tischlerhandwerk' from Northrhine-Westphalia (Germany) has proposed the European ECWins project together with 30 other partners from 8 different EU countries which has been approved to be supported by the Sixth Framework Programme of the EU in 2004.

Figure 6 Experimental testing device for measuring the window performance 'Resistance to wind-load' (© ECWINS Consortium)

33 **ECWINS Consortium** (2009). Project Deliverable 5.3 [www.ec-wins.eu]
34 **ECWINS Consortium** (2004). A European CE-based Assessment Tool for Flexible and Innovative Window Systems, Project Proposal (restricted access), European Union [www.ec-wins.eu]

The technical objectives of the ECWins project are:

- To develop a CE-Assessment Model that calculates most of the CE-performance characteristics whereby physical testing will be minimized. With this model new and individual window designs with CE marking will be become possible for SMEs.
- To develop a European Window Interface Model that assesses the applicability of CE-marked windows in specific building projects in the EU. With this model local produced windows can be designed in this way that they can be built into facades in most of the EU countries.[33]

In order to develop an 'Integrated' CE-Assessment Model, two types of Computer Models are distinguished (Figure 7). The first one is the explicit models which are used to capture calculation procedures for the six window performances: Thermal Performance, Acoustics Performance, Resistance to wind-load, Load Bearing Capacity of Safety Devices, Air Tightness and Water Permeability (Table 1). The second one is the implicit model, which provides the integration of the explicit models together with manufacturer product specifications and old test results (from test institutes or certification bodies) and creates integrated output, i.e. creates CE assessment Output (CE mark) conform the prEN 14351-1 - windows and doors - product standard. The manufacturing product specifications and the old test results are part of the data layer (Data) of the Virtual Testing Environment as discussed earlier. The implicit model will first check if there is a similar window actually which has been tested, if it is been tested it will not use the calculation procedures, but will display the previous test data. If the similar product does not exist the selected calculation procedures will be used for evaluation.[34] The Virtual Testing Environment will become available as easy-to-use Web Service for SMEs. This Web Service is currently under development (Figure 8)

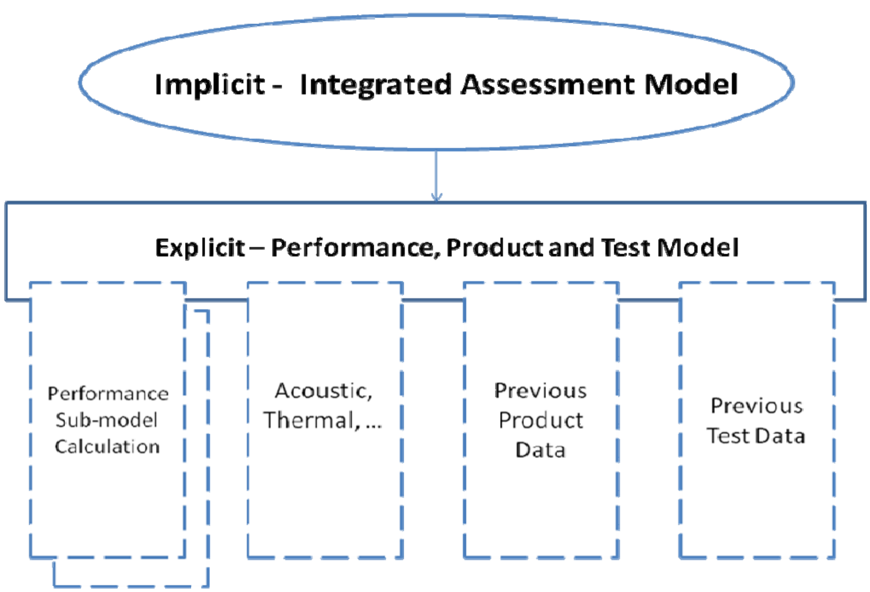

Figure 7 Integrated Assessment Model

Table 1 Explicit models which are used to capture calculation procedures for the six window performances (Thermal Performance is based on ISO 1007. Acoustic Performance is based on the work-document by Eddy Gerretsen from TNO. Resistance to Wind Load is based on the work-document by Geert Ravenshorst and Jan-Willem van de Kuilen from TU Delft. Load-bearing Capacity of Safety Devices is based on the work-document by Jan-Willem van de Kuilen from TU Delft. Water Tightness is based on a calculation model developed by Nesen Surmeli from TU Delft. Air Permeability is based on a calculation model developed by Nesen Surmeli from TU Delft).

	Performance	PURPOSE	SCOPE (procedure applied to window groups A, B, C)	VIEWPOINT
1	THERMAL PERFORMANCE	Defining the simplified calculation procedure for thermal performance	Calculation procedure for Thermal Transmittance of Windows as defined in ISO 10077-1:2006 Part-1 (Simplified method) A-B-C	Expert on Thermal Performance
2	ACOUSTIC PERFORMANCE	Defining the calculation procedure for sound insulation of a window	Calculation procedure, based on data for the acoustic performance of the composing elements of the window to estimate the sound insulation of a window of a building based on European Standard EN 12354-3:2000 A-B-C	Expert on Acoustics Performance
3	RESISTANCE TO WINDLOAD	Defining the calculation procedure for resistance to wind load	Calculation procedure for determining frontal deflection of window. A-C	Structural engineering
4	LOADBEARING CAPACITY OF SAFETY DEVICES	Defining the calculation procedure for load bearing capacity of safety devices of a window	Calculation procedure for determining forces in hinges arising from the static torsion test of a window. A-B-C	Structural engineering
5	Water Tightness	Estimating water Tightness of a window	Estimation of a window to resist water Penetration under test conditions as defined in EN 1027:2000. A-B-C	Expert on water tightness
6	Air Permeability	Estimating air permeability of a window	Estimation of the amount air passing through a window under test conditions as defined in EN 1026:2000. A-B-C	Expert on air permeability

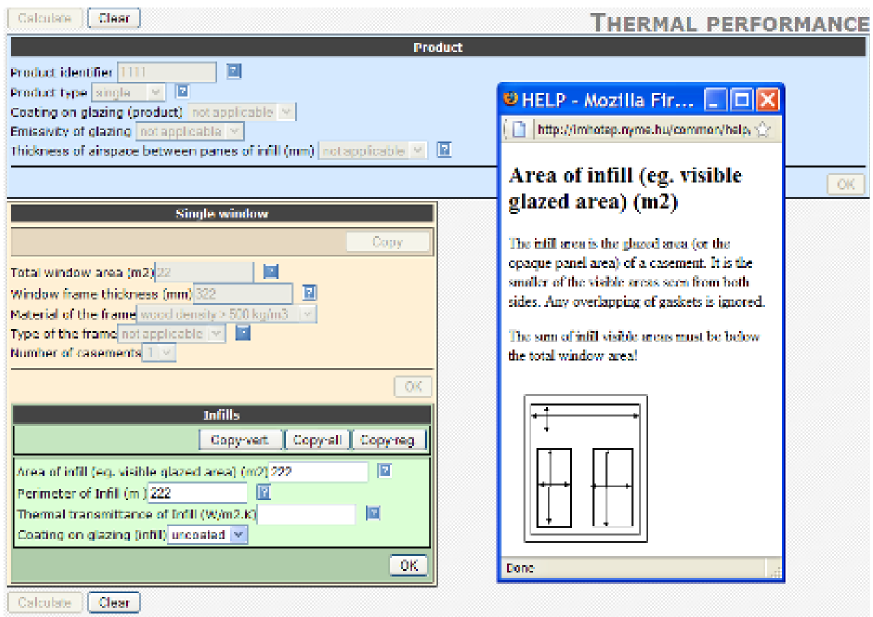

Figure 8 Web Service for performance calculations

5 Conclusions

This paper depicts the development of Virtual Testing Environments in Civil Engineering. Although some applications of Virtual Testing other than related to composite materials and components have been reported by other researchers, most effort has been put into the development of Virtual Testing Environments for composite materials and components. In this respect, Virtual Testing is based on highly-validated computer models and associated experimental data that is able to make highly precise predictions of the outcome of physical laboratory-based tests without the need to perform them in a real laboratory. In this paper, we present a conceptual scheme of Virtual Testing Environments consisting of three main layers: (1) Virtual Testing Laboratory (system layer), (2) Computer Models (application layer) and (3) Data (data layer) which are embedded in (1) Hardware Environment and (2) Software Environment. As discussed in this paper, with the promises of emerging Information and Communication Technologies (e.g. Grid Computing, Web Services, Semantic Web and Soft Computing) a whole new realm of possibilities for developing Virtual Testing Environments has opened. In this paper we discussed two research projects (at TU Delft) related to the development of Virtual Testing Environments for composite materials and components: (1) Virtual Testing Environment for cementitious materials and (2) Virtual Testing Environment for CE assessment of windows. Both projects showed the value of the application of Virtual Testing for Composite Materials and Components in Civil Engineering. In respect to the application of emerging Information and Communication Technologies, we can conclude that their possibilities are largely ignored or very limited implemented in these two research projects.

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