INTEGRATING STRUCTURAL DESIGN AND ANALYSIS THROUGH PRODUCT MODELLING

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Abstract

Application of information technology in the realisation of concurrent engineering is essential (although not sufficient by itself). A research issue in the realisation of computer supported concurrent engineering is the sharing of information between computer applications. This sharing can be achieved with product models . In the structural engineering process, two kinds of information sharing can be distinguished: the sharing with other disciplines and the sharing within the discipline (between structural design and analysis). These two kinds of sharing require two kinds of product models: a model to integrate disciplines (a kernel model) and a model to integrate activities within the discipline (a discipline view model). This paper describes a kernel model for the integration of disciplines in the building process and a view model for the integration of the activities in the structural engineering process.

1 INTRODUCTION

Improvement of the design and production process through the adoption of concurrent engineering (CE) leads to a reduction in overall costs and time-to-market and to higher product quality (Lawson and Karandikar 1994). Information technology (IT) will play an increasingly important role in the realisation of CE (Lawson and Karandikar 1994; Sriram, Logcher and Wong 1994). Several research issues need to be addressed to realise computer-supported concurrent engineering. These issues can be classified into three interaction aspects: (1) human-human interaction, (2) human-computer interaction, and (3) computer-computer interaction. This paper focuses on the third aspect, which in itself comprises several aspects, as shown by Howard (1994). Howard divides computer-computer integration into information exchange and process integration. Information exchange covers the exchange (and sharing) of data and knowledge between computer applications and process integration covers the control and co-ordination of the applications. This paper focuses on information sharing and exchange.

Sharing of product information in the building industry has to fulfil at least the following two requirements:

- The shared product information should be a complete and meaningful, computer interpretable description of the product. The product information should, for instance, include more than only geometric data.
- The shared product information should be hardware and software independent.

The required type of product information sharing can be realised with product models (Tolman et al. 1989). A product model is a computer-interpretable, complete and unambiguous description of the product being designed, constructed, and operated. This paper describes the application of product models to realise computer integrated structural engineering. The second section of this paper gives an analysis of the structural engineering process. The third section of the paper describes the models used to achieve computer integrated structural engineering. The fourth section presents some conclusions.

2 THE STRUCTURAL ENGINEERING PROCESS

The purpose of the structural engineering process is to design (and engineer) an artefact, the structural system, that is able to carry expected loads as efficiently as possible (Holgate 1986). Keywords in this description of the process are: (1) loads, (2) efficient, and (3) possible. The main function of the structural system (or load-bearing system) is to carry the *loads* that act upon the building during its existence. This should be realised *efficiently*, i.e., at low costs. Designing an efficient load-bearing system is, however, not as straightforward as it may seem from the above description. The problem is that the load-bearing system has to be as efficiently as *possible*. There are many factors that reduce the number of possible structural system designs. There has to be clear space for the people using the building. There also has to be room for windows, doors, elevators, and HVAC-systems. Moreover, the structural systems has to be constructable, durable, and easy to maintain.

This section describes the structural engineering process, its phases and stages and presents a model of the process that sets an outline for the information models described in section three.

2.1 PHASES OF THE PROCESS

Design is often regarded as a problem-solving process. Problem-solving processes can be divided into three main phases: (1) definition of the problem, (2) postulation of solutions, and (3) evaluation of the alternative solutions (Holgate 1986). Sometimes the process of choosing an alternative solution is added as a fourth phase. In this paper ‘choice’ is considered to be a part of the third phase. The three phases are also referred to as formulation, synthesis, and evaluation.

Starting point for the formulation phase is the need for a load-bearing system. This load-bearing system has to be (1) feasible, (2) safe, (3) constructable, and (4) easy to maintain (Holgate 1986). Besides these fundamental requirements there are other factors influencing the structural system. There are requirements following from other aspects of the building, e.g., from spatial and functional design and building services design. There are also requirements following from the building environment, e.g., from site location, soil conditions, adjoining buildings, and local weather conditions. Important sources for the requirements for the structural system are the client, other design disciplines (e.g., architect), the contractor, and codes, standards and regulations.

When the requirements are known, solutions to the problem can be sought during the synthesis phase. To find solutions requires a clear definition of the problem, knowledge of structural and material behaviour, and the ability to match this knowledge with the problem. Solutions can, among others, be based on standard solutions or on adaptations to solutions to similar problems. Solutions are defined by the definition of their form, which consist of a definition of the shape, material, and connectivity of the elements of the solution.

Only those solutions that meet the requirements are of interest. Whether a solution is able to meet the requirements is determined in the evaluation phase, during which the future performance of the solution is predicted. The prediction is often based on an analysis or simulation. Evaluation can be divided into three activities: (1) preparation of the analysis, (2) execution of the analysis, and (3) assessment of the analysis results (which includes the selection or rejection of the evaluated solution). The preparation comprises the construction of a correct model (physical, mathematical or conceptual) of the proposed solution and the construction of a representative future situation (e.g., loading combination) to be evaluated. The analysis results predict the response of the solution in the future situation. The predicted response determines whether the solution meets the requirements.

This paper focuses on the evaluation of the structural system against the safety requirements, i.e., on structural analysis with mathematical models. Analyses are usually not performed on the total structural system, but on elements from the system. Often, these elements are analysed with several loading combinations and in different limit states (i.e., in ultimate limit state and serviceability limit state). Moreover, analyses are performed on various level of detail, e.g., varying from analyses of the total lateral-load-bearing system to analyses of bolted joints and welds. In addition, the analyses may use various analysis methods (e.g., FEA) and various idealisations within each method (e.g., shell elements or beam elements in FEA). The analysis may also be either static or dynamic and may use elastic or plastic behaviour of the structural elements. All in all, a structural element may be analysed on many different ways and may be part of many analysis models.

2.2 STAGES IN THE PROCESS

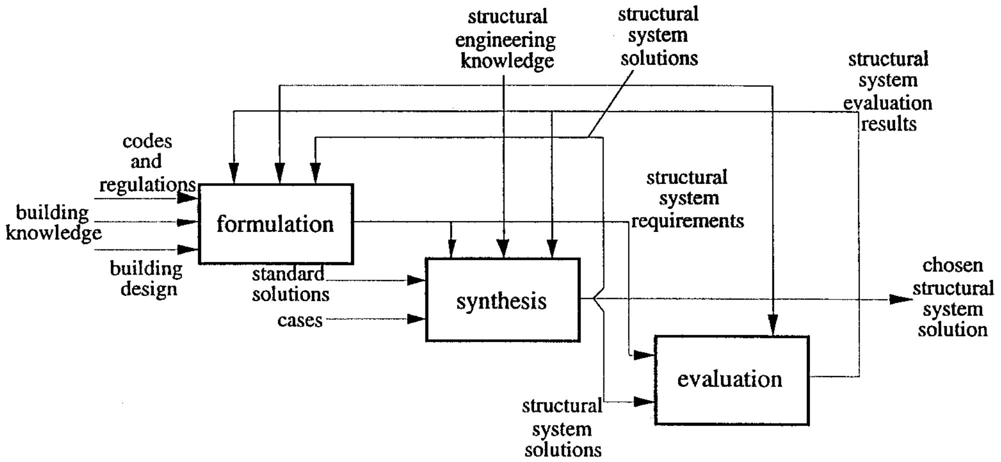

Figure 1. Model of the structural engineering process divided into three phases.

Figure 1 presents an IDEF0[1] model of the structural engineering process divided into the three phases. As the IDEF0 model shows the process is not as straightforward as might be concluded from the description above. It is a cyclic process in

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[1] ICAM Function Definition Method: a process analysis method and language (SofTech 1981)

which the problem definition gradually becomes more detailed and the implied solution becomes firmer. Each solution may imply new, more detailed requirements. Consider for instance the problem of enabling cars to cross a river. There are several solutions to this problem, e.g., a bridge, a tunnel, or a ferry-boat. Each of these solutions introduces new, more detailed requirements.

During the process the design of the structural system develops from a global solution for a global problem to a detailed solution for a detailed problem. In this development of the structural design several stages can be distinguished. Often the division in stages is based on organisational arguments, e.g., transition from one stage to the next requires an approval. The most coarse division of the process is in the stages global design and detail design. The global design stage can be further divided into outline design and scheme design. In outline design the structural principle is chosen and the location of structural elements is determined. In scheme design the dimensions of structural elements are determined and materials are specified. Finally, in detail design the joints and member interiors are specified. In each of the stages the phases formulation, synthesis and evaluation are passed through several times. In the more global stages the requirements are still vague and quantitative evaluations are difficult to make. Gui (1994) therefore suggest to make qualitative evaluations based on fuzzy requirements. Quantitative evaluations like structural analysis are mainly performed in scheme design and detail design.

3 MODELS FOR INTEGRATED STRUCTURAL ENGINEERING

In the description of the structural engineering process in the previous section two levels of integration can be distinguished. The first level is the integration of structural engineering with its environment and the second level is the integration of the separate phases and stages of the structural engineering process. The first level comprises integration with other design disciplines and integration with other life-cycle stages. The integration with other design disciplines, called inter-discipline integration, is the subject of this section. Integration of life-cycle stages, in particular of design and construction, is described in (Luiten 1994). The second level, called intra-discipline integration, is subject of this section too.

3.1 INTER-DISCIPLINE INTEGRATION

The history of product model research shows that it is difficult to find *the* product model, i.e., the model that is able to integrate the total building process. Each participant in the process has his own view on the product and therefore requires his own set of information. Consequently, the focus of the research community has shifted to the development of models that are able to cope with these different views (e.g., (Amor and Hosking 1993; Rosenman, Gero and Huang 1993; Tolman, Nederveen and Bakkeren 1993)). The approach of Tolman, Nederveen and Bakkeren consists of view models for each relevant discipline and a kernel model. Each view model integrates the discipline internal activities and applications. The kernel model integrates the different view models (see also (Nederveen 1993; Bakkeren and Tolman 1994)). The kernel model is hidden for the users of the model because each discipline has access to it via its view model. Therefore, the users of the model don't need to agree on the contents of kernel model: they only need to agree on their own view model. Development of the kernel model can be left to the research community. Its main requirement is that it is able to integrate the view models.

3.1.1 Systems Approach for the Building Kernel Model

For the building kernel model the systems approach is adopted. Modelling buildings as a collection of systems is a common way of modelling used in the RATAS project (Björk, Penttilä and Hannus 1989), by Turner (1988), and by Lavakare and Howard (1989). The approach by Tolman, Nederveen and Bakkeren (1993) has two important characteristics: (1) the building is first decomposed into aspect systems and (2) the interrelations between the aspects systems are modelled explicitly. A building aspect system is a collection of building elements that together perform a certain function (e.g. load bearing) and that are all of the same type (e.g., structural elements). Examples of building aspect systems are the space system, the space separation system, the heating system and the structural system. Each system is modelled in a separate conceptual model, which precludes complexity of the models. Notable is that design disciplines usually contribute to the design of a few building aspect systems only. The structural engineer for instance contributes to the structural design only. Due to this most problems occur where building systems interrelate (Rush 1986). The description of the structural engineering process also showed that it is important for the structural engineer to know where the other design aspects interfere with the structural system. Because of the importance of the system interrelations they are modelled explicitly in the building kernel model.

For the development of the conceptual building kernel model (i.e., a model of the class of buildings) a generic conceptual product model is used. This generic model is based on the General AEC Reference Model (GARM) (Gielingh 1988) and the IMPPACT[1] Reference Model (Gielingh and Suhm 1993), which is also based on the GARM. The generic model is developed within the PISA project[2] and is described in (Gielingh et al. 1994). Figure 2 presents a NIAM[3] diagram of a simplified part of the generic model. The most generic entity type is called Object[4]. There are several orthogonal specialisations of this entity type. Only those of importance to the building kernel model are shown. One specialisation results in a Required Object and a Proposed Object. A Required Object can be fulfilled by several Proposed Objects and a Proposed Object decomposes into Required Objects. This modular decomposition mechanism is based on the Functional-Unit/Technical-Solution (FU/TS) principle of the GARM. Another specialisation direction results in the distinction between the entity types Property, Concept, and Port. Concepts have Properties (e.g., material, shape, and location and orientation) and Ports. Ports are linked through Interfaces. The Port-Interface construct enables modularity in the modelling of connectivity. From a third specialisation direction only the subtype Product is used.

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[1] ESPRIT Project 2165: Integrated Modelling of Products and Processes using Advanced Computer Technologies

[2] ESPRIT Project 6876: Platform for Information Sharing by CIME Applications

[3] Nijssen's Information Analysis Method: an information modelling method and language (Nijssen and Halpin 1989)

[4] In the PISA Product and Process Model this entity type is called Definition. However, since the model is intended to be used for modelling products and processes (Gielingh et al. 1994), i.e. things and not information about things, the term Object is considered to be more appropriate.

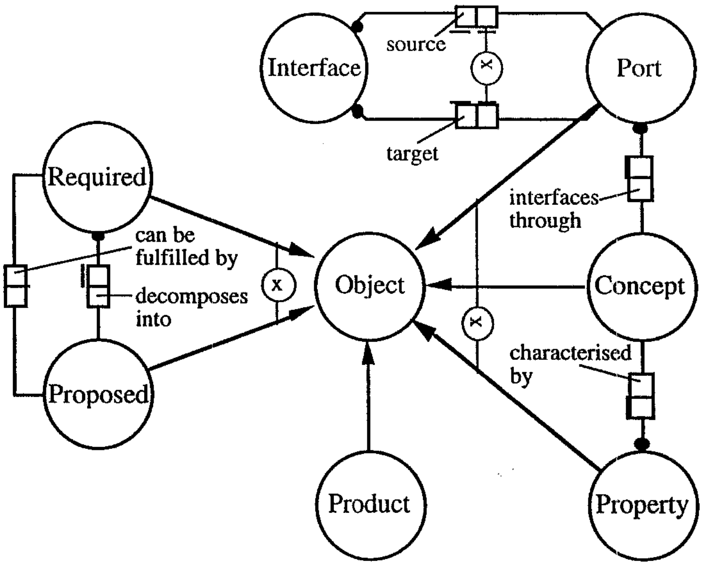

Figure 2. Part of the PISA product and process model that is used for the development of a building kernel model.

Figure 3 presents a model that reflects the systems approach used for the building kernel model. The distinction between Required and Proposed Objects is not shown. The combinations that are used are Product-Concept and Product-Port and are denoted by a circle enclosed by a square, which means that these entity types are referenced and are defined in another diagram. A Building has Building Ports, e.g., to interface with the site, and consists of Building Systems, which have Building System Ports. Building Systems consist of Building System Elements, which may consist of other Building System Elements. Building System Elements have Building System Element Ports. There are two kinds of Element Ports: the System Internal Port and the System External Port. The System Internal Port interfaces with another System Internal Port from the same system and the System External Port interfaces with another System External Port from another system. The System External Ports model the system interrelations, which are relations between elements from different Building Systems. By defining an ontology for building ports the interrelations that occur in a building can be classified. Thus the type of a System External Port provides information to the designers of the separate building systems. There are several directions in which ports can be specialised, e.g., according to their topology or to their function.

3.1.2 Structural System Model in the Building Kernel Model

In the structural engineering process the focus is on the structural system and its interrelations with other building systems. Figure 4 presents the model of the structural system. The Structural System is one of the Building Systems. A Building has exactly one Structural System. The Structural System consists of Structural Elements, which interface through Structural Element Ports. The Structural Element Ports are either internal or external, depending on whether they interface with another Structural Element Port or a System Element Port from another system. Possible subtypes of the Structural Element Port are the support port and the penetration port. The support port is a port that transfers forces from one structural element to another. A penetration port can be used to specify an interference between the structural system and the HVAC system that requires an opening in the structural element.

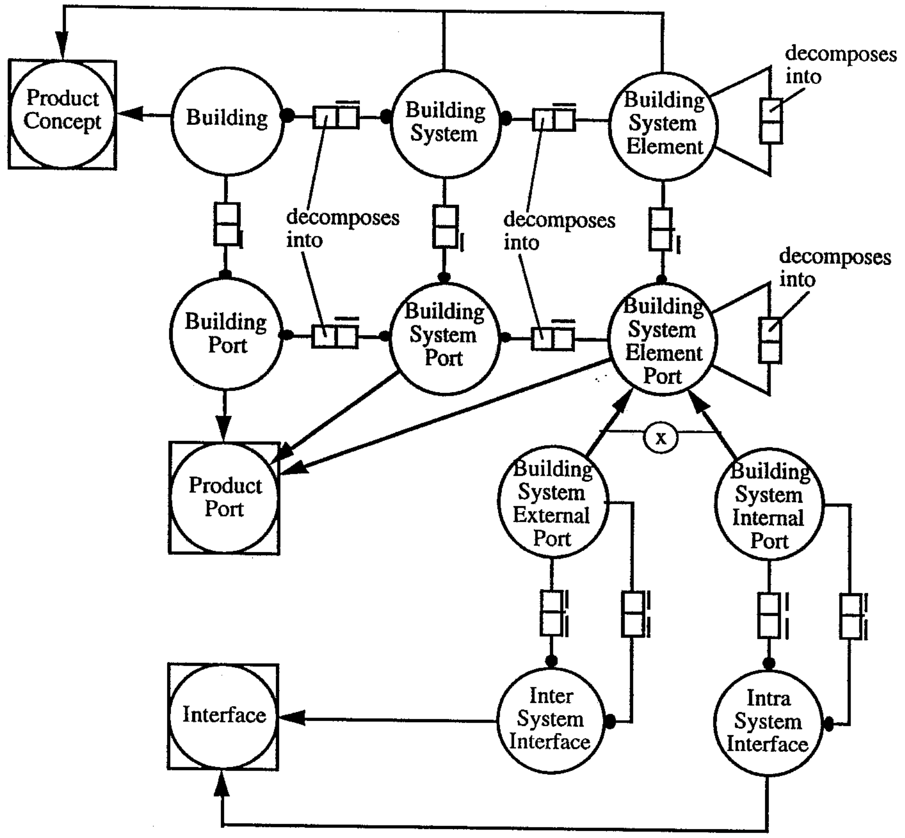

Figure 3. Model of the systems approach used for the building kernel model. Squares denote referenced entity types.

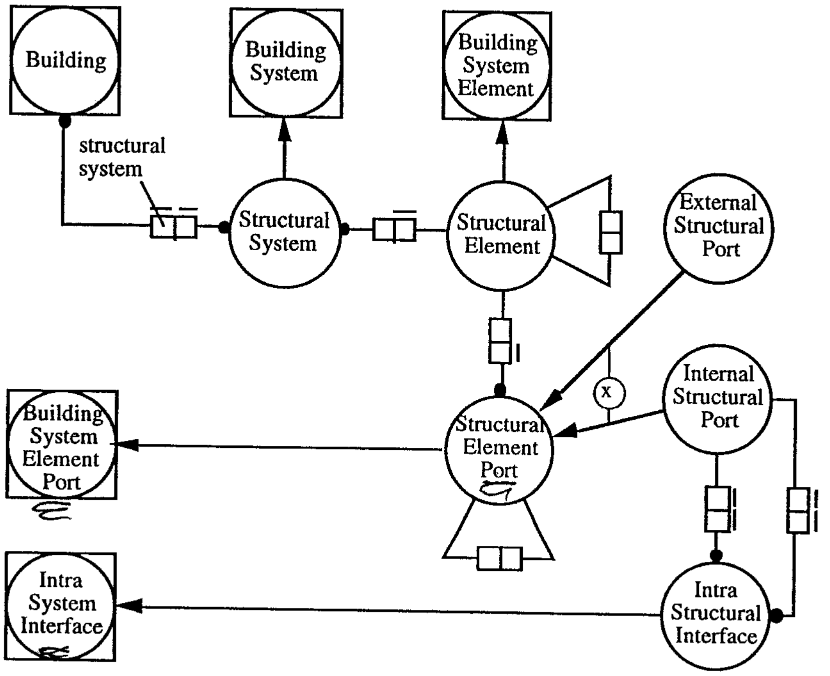

Figure 4. Model of the building structural system.

The model of Figure 4 contains two structural entity types: the total structural system and the structural element. Through the recursively defined decomposition relation on Structural Element, multiple decomposition levels are possible. Several existing structural system models contain a number of predefined decomposition levels. Unfortunately each of these models uses its own terminology. In STEP[1] application protocol 225 (ISO/TC184 1994)[2] the following levels are used: assembly, element, composite component, and component. Components are defined as the constituent shapes of the elements. Components can be aggregated into composite components and into elements. Elements can be aggregated into assemblies. Examples of elements are beam, column, wall, and slab. In the Building Information Model (BIM) (IOP-Bouw 1989) the following two levels are present: assembly and part/feature. Assemblies consist of other assemblies and finally of parts, which are the atomic elements in the structural system and have features. The same levels can be found in the CIMSTEEL model (Crowley 1993). A special kind of assembly in the CIMSTEEL model is the structural member, which is the lowest level of assembly and can be compared to the element of AP 225. The building structural systems model (BSSM) (ISO/TC184 1990) also uses two levels: assembly and element. Assemblies decompose into other assemblies and finally into elements. Because most of the models lack clear definitions of their entity types it is difficult to assess the differences and similarities. Table 1 tries to compare the models by classifying some examples of structural elements under the entity types of the models.

The most important characteristic of all the atomic entity types of the different models is that they are the entities that have shape and material. All higher level entity types are merely aggregations of the atomic types. The models differ in the number of types for the higher levels. The BIM and the BSSM only contain the entity type Assembly. AP 255 and the CIMSTEEL model also use the type Assembly, but they have a special type for the lowest level assembly that consists of atomic types only. AP 225 uses the type Element and the CIMSTEEL model used the type Member.

AP 225	BIM	CIMSTEEL	BSSM	Example
Assembly	Assembly	Assembly	Assembly	Frame, Truss
Element	Assembly	Member	Element	Beam, Column, Slab
Composite Component				Reinforcement Cage
Component	Part, Feature	Part, Feature		Steel Profile, Reinforcement Bar, Hole, Bolt, Weld

Table 1. Comparison of the decomposition in the structural system models.

Figure 5 presents a model that combines the different constructs of the models described above. It distinguishes 3 subtypes of Structural Element: Structural As-

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[1] Standard for the exchange of product model data, ISO 10303.

[2] The scope of part 225 (Application protocol: Structural building elements using explicit shape representation) is not restricted to load-bearing structural elements but includes all physically discrete constituents of a building structure.

sembly, Structural Part, and Structural Component. Assemblies may consists of other Assemblies and/or Parts. A special kind of Assembly is the Connection, which connects two or more Assemblies. A Structural Part consists of Components, which are the 'atomic' elements in the structural system. A special kind of Part is the Structural Joint, which joins two or more Parts. Components can be either Complex (e.g., reinforcement cage) or Primitive (e.g., reinforcement bar). Figure 5 also shows two other subtypes of Structural Component: the Joint System (e.g., bolt system) and the Feature (e.g. a hole).

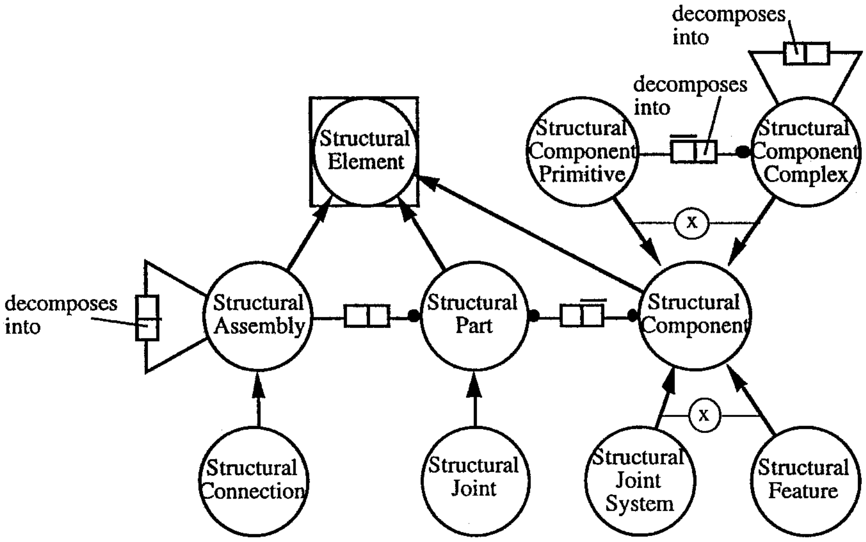

Figure 5. Specialisation of the entity type Structural Element.

3.2 INTRA-DISCIPLINE INTEGRATION FOR STRUCTURAL ENGINEERING

Based on the structural system model in the conceptual building kernel model a structural engineering view model is developed. The objective of this view model is the integration of the different activities that constitute the structural engineering process. Consequently the view model reflects the structure of this process. This section describes the models that integrate the structural engineering process.

3.2.1 Structural Engineering Formulation and Synthesis

The cyclic nature of the design process in general is captured in the GARM by the FU/TS-decomposition mechanism. This mechanism is also part of the PISA product and process model. The mechanism is used to integrate the formulation and synthesis phases (see Figure 6). In Figure 6 the Structural Concept is used as the generalisation of all entity types that belong to the structural system: it is the supertype of both the Structural System itself and the Structural Element (see Figure 4). The Required Concept has Required Properties, which may be found in a Requirement Library like building standards. Important requirements for the structural system are those that should be met in the ultimate limit state and the serviceability limit state and are prescribed by national or international codes, e.g., the Dutch codes for loadings and deformations (NNI 351 01 1991). The Required Concept also contains references to Imposed Loads that are prescribed by codes. The life load on a floor slab for instance is prescribed in (NNI 351 01 1991) and depends on the function of the space above the floor. This information has to be captured in the interrelations between the space system and the structural system. The Required Concept interfaces through Required Ports.

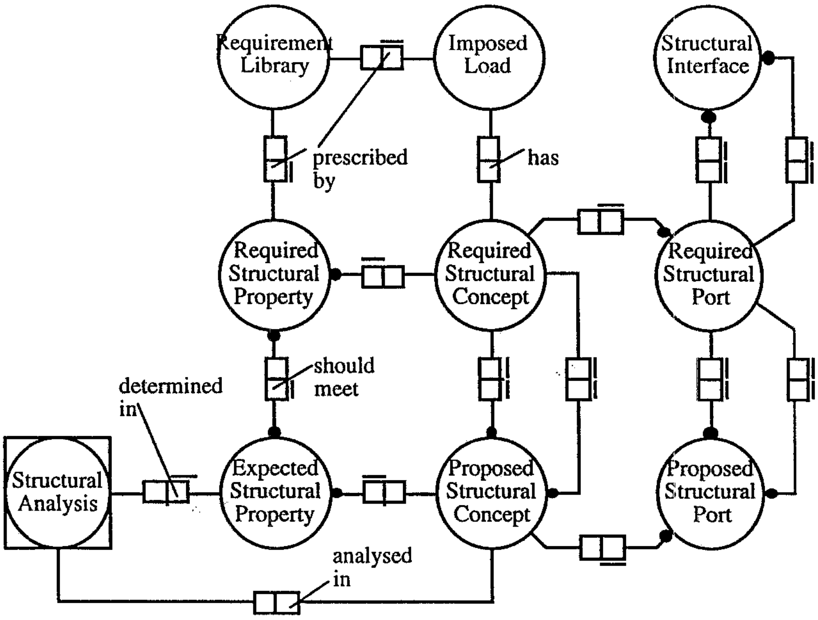

Figure 6. Model for the formulation and synthesis phases.

The FU/TS-decomposition mechanisms is applied to both the Concepts and the Ports. The Required Concept can be fulfilled by Proposed Concepts with Expected Properties. These Expected Properties should meet one of the Required Properties and can be determined in a Structural Analysis (e.g., the deflection of a beam) or be taken from a property library (e.g. the specific gravity and Young's modulus of structural steel). Proposed Concepts interface through Proposed Ports. Proposed Ports are not directly interfaced to each other, i.e., there are no Interfaces that link Proposed Ports. The interface is only established between the Required Ports to which the Proposed Ports belong (see also Figure 7). This prevents redundancy and assures modularity (Willems and Tolman 1993).

The Proposed Port can be used to take into account the reaction forces on a structural element that followed from a structural analysis. In the example of Figure 7 the two ports of the beam have to supply a reaction force to the q-load. This reaction force is transferred by the ports and the structural joint to the column. The column should be able to carry this reaction force: the reaction force belongs to the column's requirements. Because proposed ports are not interfaced to each other directly, the reaction force is only accessible through the interfaced required ports (see Figure 7). The same mechanism can be used for the transfer of displacements and rotations. The mechanism can also be used to keep track of the dependencies between features of parts and joint systems in joints. A bolt system, for instance, requires a hole pattern in the steel profile of a beam. These dependencies are modelled explicitly in (Gelder 1989), (IOP-Bouw 1989), and (Crowley 1993).

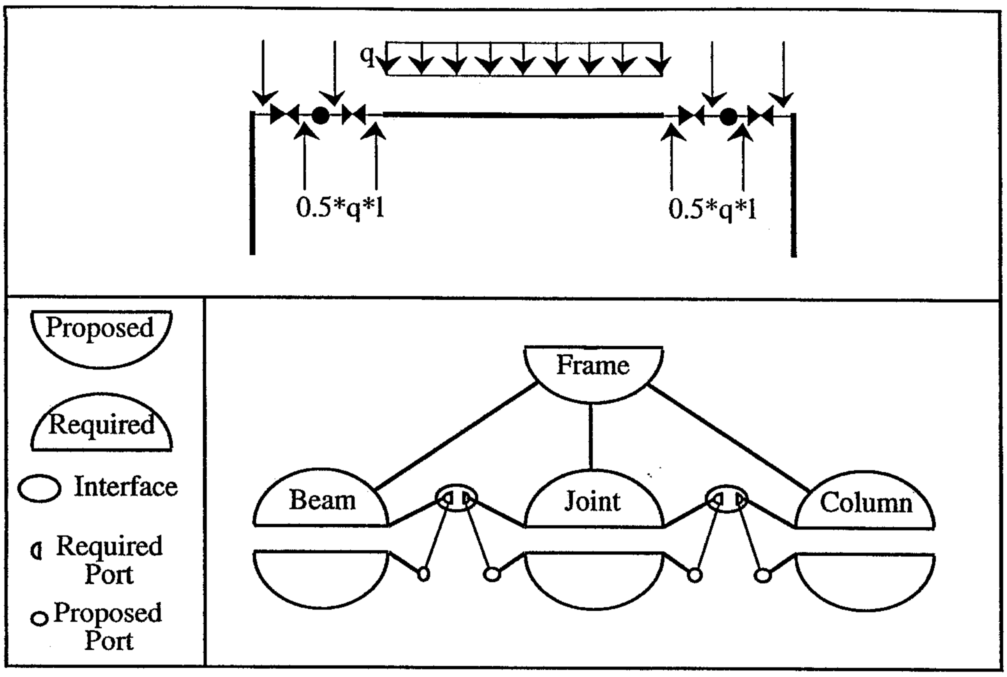

Figure 7. Transfer of reaction forces through ports (denoted by arrows).

3.2.2 Structural Engineering Evaluation

As modelled in Figures 2 and 6, a Required Concept can be fulfilled by many Proposed Concepts. During evaluation the structural engineer determines which proposals are able to meet the requirements and selects proposals based on the evaluation results. To evaluate proposals, the structural engineer needs to know how the proposed structural system or element will behave under certain conditions. To determine this behaviour, structural analyses are performed. Figure 8 presents a model for the evaluation phase, which is based on the GARM. Expected Properties are determined in Structural Analyses. Based on the results of these Analyses, Decisions are taken on the Status of the Proposed Concept.

A proposed beam, for instance, has to meet at least the following two requirements: (1) an ultimate-limit-state requirement (safety against failure) and (2) a serviceability-limit-state requirement (maximum deflection). Whether the proposed beam meets these requirements is determined with structural analyses. When the beam meets both requirements, the structural engineer can decide to select the proposed beam. Its status is then changed to selected.

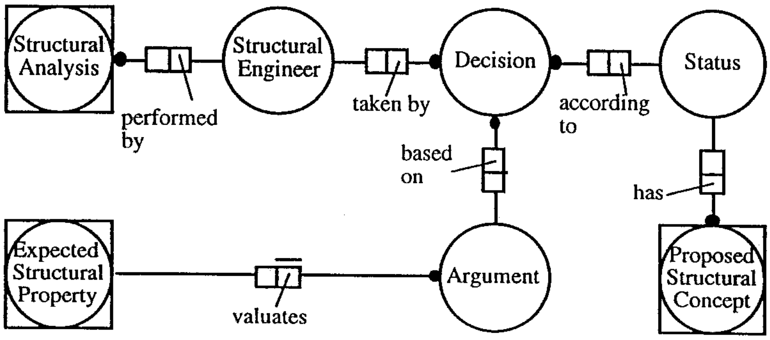

Figure 8. Model for the evaluation phase.

Figures 6 and 8 use the referenced entity type Structural Analysis. The process of structural analysis constitutes an important part of the evaluation phase. Section 2 of this paper describes the division of the analysis process in the sub-activities preparation, execution, and assessment. The execution is usually performed by a computer application, e.g., a FEA application. The preparation and assessment are done by the structural engineer, possibly supported by an (intelligent) application. Both preparation and assessment require structural engineering knowledge, which can be captured in knowledge bases (Thomas, Maanen and Mead 1989; Roy, Bharadwaj and Ludden 1994).

Several models have paid attention to the integration of structural synthesis and analysis. Examples are the BIM (IOP-Bouw 1989) and the CIMSTEEL model (Crowley 1993). The integration of synthesis and analysis in these models does not seem flexible enough to cope with all the different kinds of analyses described in section 2. Besides, these models mainly integrate FEA. As shown in section 2, and also stated by Karlshøj and Damkilde (1992), the model should be independent of any analysis method. Willems (1987) therefore suggest to use an intermediate model that contains analysis-method-independent idealisations of the structural elements to be analysed (e.g. joints idealised to hinges), boundary conditions, and loading combinations that act upon the elements. From this intermediate model FE-representations or other representations can be derived.

Figure 9 presents the top level of an intermediate model for structural analysis. A Structural Analysis consists of a Structural Analysis Model, which is the complete description of the idealised structural elements. A Structural Analysis also consists of Boundary Conditions (i.e., the supports), Loading Combinations, and Analysis Results. Decisions on the status of proposed solutions are based on analysis results (see also Figure 8). It is important to be able to trace the analyses on which decisions were based. Question that may arise are: (1) was the idealisation correct, (2) which analysis method was used, (3) was the loading combination representative, and (4) were the results interpreted correctly? All this information has to be captured by a more detailed model for structural analysis. Such a model is outside the scope of this paper.

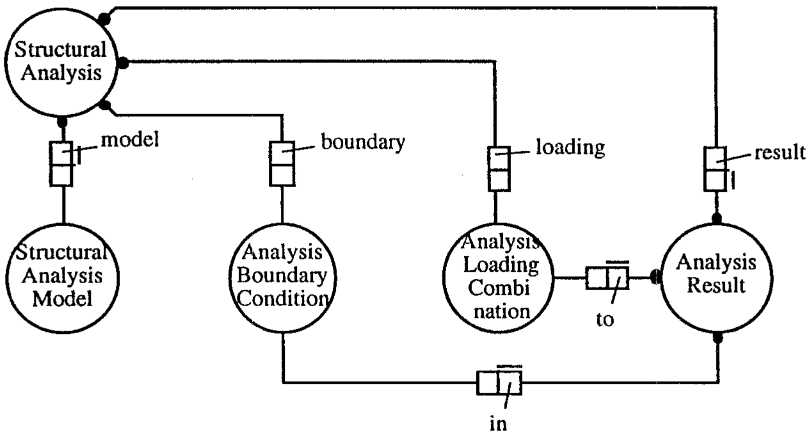

Figure 9. Top level of the model for structural analysis.

3.3 APPLICATION OF THE MODELS FOR INTEGRATED STRUCTURAL ENGINEERING

In a project for the Dutch Ministry of Public Work and Transport the disciplines of flyover design and flyover structural engineering were integrated using two view models and a flyover kernel model. Information from the discipline of flyover design was passed on to the structural engineering discipline through the kernel model. From the structural engineering model the flyover-deck could be selected for structural analysis. To this selection loading combinations and boundary conditions were added (partly automatically). From this analysis model a FE-representation was generated automatically (see also (Bakkeren and Tolman 1994)).

4 CONCLUSIONS

This paper describes an approach to computer integrated structural engineering. The approach uses product models to achieve the integration. The integration contains two levels: inter-discipline and intra-discipline integration. In the approach two models are used: a structural engineering view model to achieve intra-discipline integration and a kernel model for inter-discipline integration. The kernel model uses a systems approach to model buildings. The interrelations between the building systems are an important aspect of the kernel model. The structural engineering view model reflects the structure of the structural engineering process: it follows the division of the process in formulation, synthesis, and evaluation. The view model also models the relations between the structural system design and the many structural analysis need to evaluate the design.

The approach was used in the integration of flyover design and flyover structural engineering. In this project inter-discipline integration was realised through the exchange of a complete, unambiguous, meaningful flyover kernel model. Also the preparation for FEA using information contained in the structural engineering view model was supported. In the project only a small portion of the total integration is realised. The exchange is from design to engineering and from engineering to FEA only. Analysis results can not be reused and required design changes can not be added to the model by the structural engineer. Version management and conflict resolution were outside the scope of the project.

5 ACKNOWLEDGEMENTS

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