ASSESSMENT OF IFCS FOR STRUCTURAL ANALYSIS DOMAIN

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EDITOR: B.-C. Björk

Caiyun Wan
School of Civil and Environmental Engineering, Nanyanag Technological University, Singapore
email: pg01423884@ntu.edu.sg

Po-Han Chen
School of Civil and Environmental Engineering, Nanyanag Technological University, Singapore

Robert L. K. Tiong
School of Civil and Environmental Engineering, Nanyanag Technological University, Singapore

SUMMARY: *This paper presents the findings from the collaborative research project between Nanyang Technological University and Singapore Institute of Manufacturing Technology which aims to explore the integration and interoperability between structural design and architectural design applications based on IFC standards and product model. Industry Foundation classes (IFC) have made substantial progress in recent years, and many design software companies now provide export capabilities of IFC based product models. But to date, there has been virtually no assessment and validation of how well the IFCs can support structural analysis. So in this paper after a brief introduction of this project, the information requirements of SAP2000 from software point of view are analyzed. Based on the comparison between the information requirements and current IFC models, the capabilities of IFC product models to support structural analysis at multiple levels of detail are assessed. It is found that IFCs still do not captured explicitly and provide a representation for some information, such as prestress load and types of load combination etc., which means that some improvements to current IFCs may be necessary. Thereby, at last some suggestions on IFC extensions model development for these information gaps are proposed in the paper.*

KEYWORDS: *Industry Foundation Classes; Information Modeling; Process Modeling; International Alliance for Interoperability*

1. INTRODUCTION

In the AEC (Architecture, Engineering and Construction) industry many project models have been designed and proposed for solving the multidisciplinary problems of information integration. Eastman (1999) divided current building product modeling efforts into two categories, aspect models that address a specific domain in the building industry, and framework models that address the whole structure of a building. Some building aspect models that make use of several STEP technologies: the LPM (Logical Product Model) in CIMsteel project (Watson and Crowley, 1995), the central building model (IDM) in COMBINE (Dubois and Flynn, 1995) and Part 225, the STEP AP that describes the building elements using explicit shape representation (ISO, 1999). In these projects they also developed prototype product model environments to prove the validity and effectiveness of the approach and stimulate further research, standardization and implementation activities. The framework model is like Part 106, the STEP Building Core Construction Model (BCCM) (Wix, ISO, 1996). By a common communication medium, the European Union ESPRI III project, COMBI (Computer-Integrated Object-Oriented Product Modeling Framework for the Building Industry) (Scherer, 1995) carried out the exchange of data between the different design tools. Bentley's Building Information Modeling (BIM) is a new approach to how architects, engineers, contractors, and owner-operators use information technology on building projects. Powered by 20 enabling technologies, BIM improves the way building professionals work and collaborate by elevating the dialog to one of information, rather than just graphics (Bentley, Khemlani, 2003).

Recently the two most important international standards for integrating all AEC information models are the ISO STEP and IFC, defined by an international organization called IAI. To promote exchange and sharing of information in the AEC industry, IFC defines a set of standards similar to those AEC-related standards of ISO STEP. Currently IFCs become the most widely accepted and supported standard data model by the AEC/FM industry and many design software companies have provided export capabilities of IFC-based product models. Up to now the version IFC 2x Edition 2 has been released whose domain coverage includes architecture, HVAC, FM (Facility Management), Construction Management, Building Controls, Plumbing Fire Protection, Structural Elements, Structural Analysis and Electrical Domain (IAI, 2003). IAI/IFC has created a new breed of implementation attempts. For example, BLIS (Building Lifecycle Interoperable Software) project was conceived as a way to initiate the next logical phase in the widespread adoption of an object data model standard for the AEC/FM industry (BLIS, 1999). BLIS is a coordination project -- coordinating the implementation efforts of vendors seeking to support IFC R2.0 in applications. ToCEE (Towards a Concurrent Engineering Environment) developed a client multi-tier server system for concurrent engineering (Scherer, 2000). It follows the STEP methodology and is based on IFC-V1.5. Information Networking in the Construction Process (Vera) is a technology programme of Tekes, the National Technology Agency of Finland (Froese, 2002). It aims to promote the implementation and use of information technology and networks and to make it possible to manage the information flows during the entire lifecycle of the building. Under this circumstance, in order to explore the integration and interoperability between structural design and architectural design applications based on the IFC standards and product models, a collaborative research project has been initiated between Nanyang Technological University and Singapore Institute of Manufacturing Technology (SIMTech).

2. THE NTU/SIMTECH COOPERATIVE RESEARCH PROJECT

2.1 Goals of the project

The objectives of this project include (1) to study the feasibility and methodology for the development of IFC-compliant building information models, (2) to prepare core technologies for the implementation of building model servers, and (3) to demonstrate conceptually the usage of the information modeling methodology and the model server technology for exchange of application-specific information over the Internet by a prototyping model server.

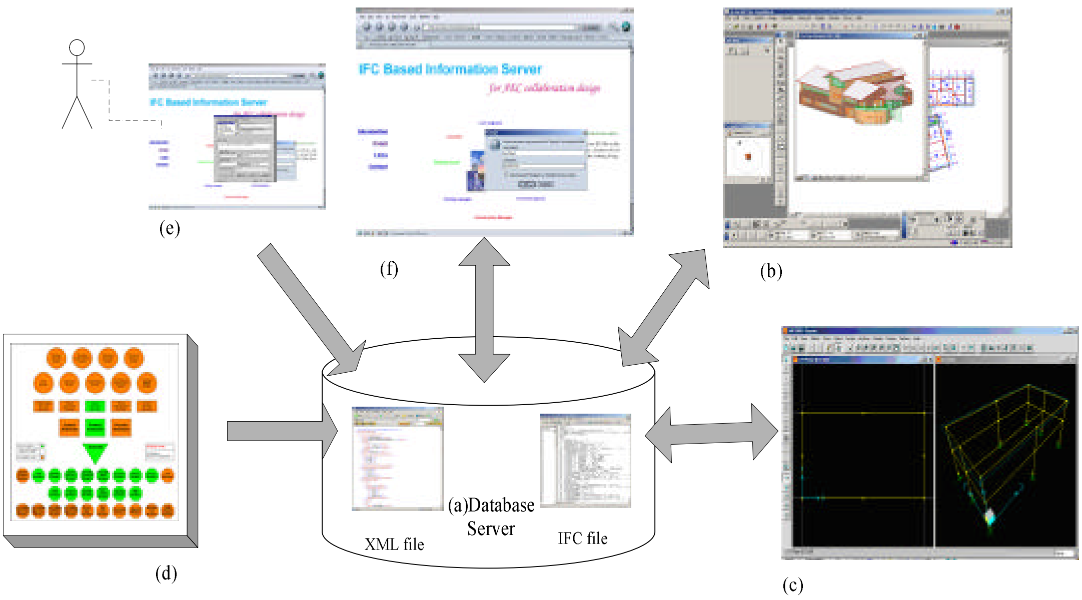


FIG. 1: Structure of Building Model Server (a) Model sever; (b) Architectural design application; (c) Structural analysis application; (d) IFC standards and product models; (e) Engineer enter information; (f) Web-based application.

In this project a model server is developed to support both IFCs based data integration and transaction-based interoperability between the architectural design and structural design applications. Fig. 1 shows the structure of the model server and Fig. 2 is the use case diagram in Unified Modelling Language (UML).

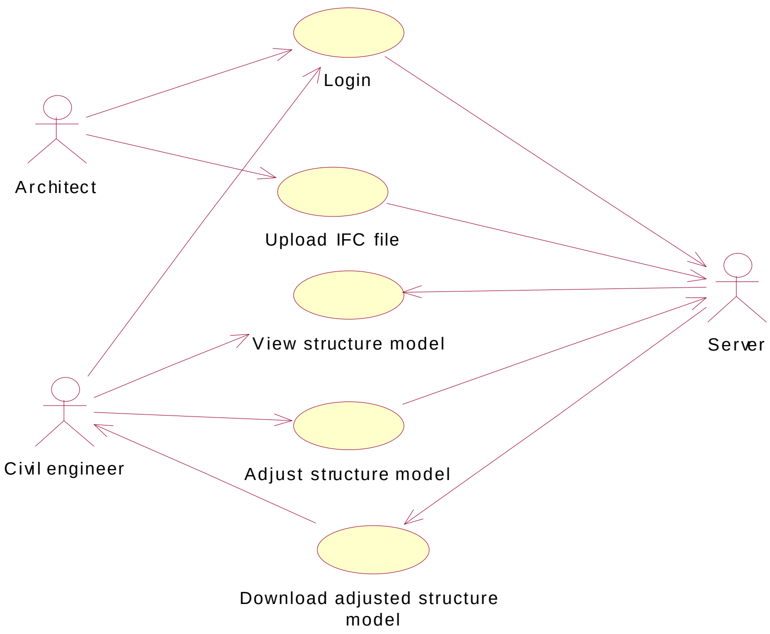


FIG. 2: The User Case of The Software System

A typical use scenario involves both architects and civil engineers. First architects login the server via a browser. The server recognizes the architect and assigns him with a role. Architects submit the architecture design in IFC format to the web application server via the web page. The programs on the server retrieve the geometric information of structural elements, such as beams and columns, from the submitted file. Based on the information, connectivity among structure elements is deduced. Joints between the connected structure elements are then created. A structure analysis model is generated and outputted in a XML format, which is also displayed in the Java-based viewer embedded in the web page to the structural engineers on the client side. In order to improve the interoperability, it allows the structural engineers on the client side to modify the structure analysis model. The modification is sent back to the server and the corresponding changes are made on the structure analysis model. Finally the structure analysis model, with the information from both architects and structural engineers, is made available on the web page. In this project, the architectural design comes from ArchiCAD. The structural related information will be transferred to SAP2000 for structural analysis. However, SAP2000 can not support the IFC file format directly, so an intermediary text file, S2K which can be read by SAP2000, is needed. That is, a transformation between the information in IFC file and the information in S2K file is necessary.

During the translation between these two different formats, we found that some information is defined in different ways which need be inferred from the data in IFC models and some information can not be found the corresponding definition in current IFC models. It is possibly because initially it is not an implementation project, IFC models are much more from an expert's perspective rather than from the actual software operation. Although the structural analysis domain knowledge has been incorporated into the current release of the IFCs, but to date, there has been virtually no assessment and validation of how well the IFCs can support structural analysis. All these problems stimulate the work to find the information in different definitions between SAP2000 and IFC models, find the information needed by SAP2000 but missed in IFC models, as well as confirm whether it is necessary and how to do some extensions for current IFC models. So the focus of this paper is on assessing and developing the structural analysis information models. Based on the modelling for the information requirements of SAP2000's structural analysis process, the capability of current IFC models for structural analysis domain is assessed by comparing the requirements with IFC models. It goes further to propose some IFCs extensions for the structural analysis domain.

2.2 Relationship to IAI ST Projects

Up to now there are four IFC projects related to the structural field, ST-1, ST-2 (Yasaka and Furukawa, 2002), ST-3 (Karstila, 2002) and ST-4 (Liebich etc., 2002). Fig. 3 illustrates the relationships between our project and these four IFC projects.

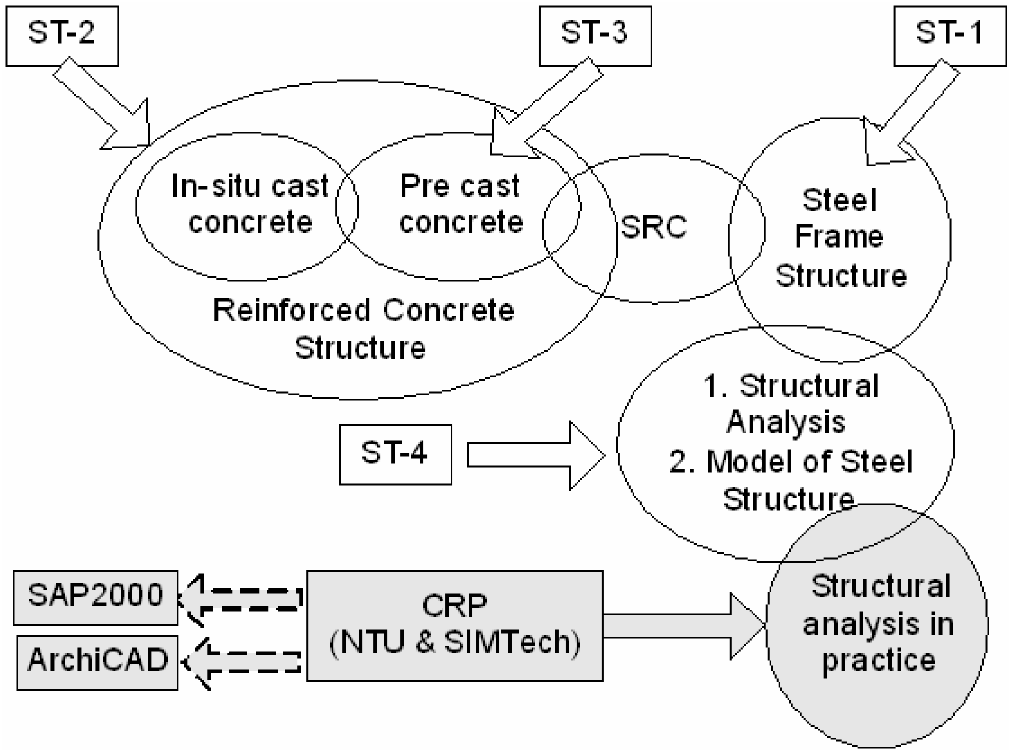


FIG. 3: Relationships with other IFC Structural Projects

In the IAI organization, the steel frame constructions model development project named ST-1 and ST-3 the precast concrete structural model project were both taken charged by the Nordic chapter. The German chapter started the project for the structural analysis and model of steel constructions named ST-4. ST-2 emphasized modeling the basic structural design and structural execution design. Basically, our project is completely different with ST-1, ST-2 and ST-3 projects. Firstly we focused on different domains, such as our project is mainly on the process from architectural design to the finish of structural design. But ST-3 project covers the whole life cycle of precast concrete construction, from design, manufacture to installation. Secondly maybe we have different objects, like only precast concrete construction studied in ST-3 project and steel frame structure for ST-1. Considering the direct benefit for local market, the reinforcement concrete in-site construction is decided as the study object of our project. At last we studied different processes. ST-2 covers basic structure design and structural execution design. However in current stage the primary aim of our project is to integrate structural analysis with architectural design. In the future design process will be considered. In a word, our project will not reduplicate the work of ST-1, ST-2 and ST-3 projects. There is no any direct relationship between them. Just to some extend our project will use the extensions developed by these three projects.

The most relevant project is ST-4. Part of our modeling the research aims is very similar. But it is different on our final levels of implementation. The IFC models of ST-4 are much more from an expert's perspective rather than from the actual software operation. In Vol. 0 of ST-4 project documentations (Horenbaum, 2002), there are totally 10 specific scenarios listed, which don't include the data sharing between architect and structural engineer. So to some extent, this project gives a real meaning to the integration of architectural design and structural design. There should be some deficiencies existed in the proposed model for the real application. Not only it may possibly miss some entity need to include, but also it may miss some attributes for defined entity either existed or extended, for instance, the types of load combination or principal forces and moments are not considered in the model.

2.3 Scope of the NTU/SIMTech Project

Architectural design and structural design is a broad and complex process. Since the architecture information has maturely defined in IFC and much commercial software have been able to generate IFC file, the scope of the project focuses on the portion of structural analysis process. However, the initial planning, including a rough specification of design requirements, is assumed to occur prior to conceptual design and is outside the scope of the study. A user scenario is assumed that the work process of a structural engineer starts with examining existing architectural information. Type of structure that will be analyzed is of a frame type with its elements in planar (2D) and spatial (3D) dimension. The structural analysis is limited to static structural analysis and design for reinforced concrete structure using SAP2000 software. For architectural design, the supporting software used is ArchiCAD. The information model is referred to IFC release 2x Edition 2.

3. IDENTIFICATION OF SAP2000 INFORMATION REQUIREMENTS

3.1 Developing Generic Structural Analysis Models

Fig. 4 shows the integrated process and information modelling flow, as well as the methodology used during the model developing.

The research starts with the definition of the scope of the model's applicability. A well-defined scope not only provides the boundaries of the application domain, but also serves as a guideline for evaluating the "completeness" of the information model. Whereafter the requirements analyzing and modeling is conducted. During this course the IDEF0 is selected as the process modeling methodology. The information requirements is abstracted and modeled directly from the IDEF0 process models, and expressed to IDEF1 information model. This information model is obtained from process models and all the information is process related. And this information model is intended to be independent of any physical implementation and be sufficiently explicit which can fully describe the data needs of the application. These information models can be the basis to define a standard product model.

Based on the general information model and concept of IFC, a standard product model for the discoursed domain will be proposed. In this project it is not necessary to modeling the whole domain. After the comparison with the existing IFC Release, only the information missing is searched and necessary IFC extensions are developed. In the next section this paper will follow the work processes shown in Fig. 4, step by step, to make an assessment on the capability of current IFC models to support structural analysis from software viewpoint.

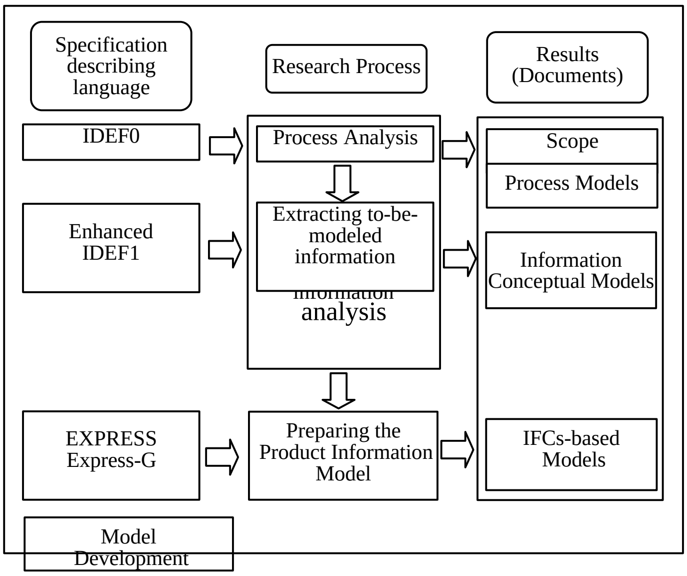


FIG. 4: Integrated Process and Information Modelling Flow

3.2 Identification of SAP2000's Information Requirements

Identifying the information requirements is an important step in the IFC extension modeling process. According to the flow in Fig. 4, at first numerous process models at different levels are set up. Here it is not necessary to reveal all the detailed process models. Only the top level processes of building design which is a brief introduction and a direction to do further decomposition and analysis is given in Fig. 5. The high-level model described in Fig. 5 helps to achieve a basic structure on which a particular system, together with its applications, could be built as a layered architecture. This model should facilitate the endeavor towards integration of the structural design process and systemization of the structural design information. Among them, the activities in shadowed boxes have been analyzed completely in this research.

Based on the process models, process-oriented information modeling methodology is used to develop the information models, to extract all the information requirements and to express them in an enhanced IDEF1 model. This methodology is an integration of process models and information models [Wan, 2003]. According to the conversion rules presented in this methodology the information model can be obtained from process models directly. All the information needed by SAP2000 to do structural analysis can be classified into 5 different categories by their functions: (1) geometry information; (2) material information; (3) load information; (4) member section information; (5) other information. The advantage of these classifications can make information more clear because they have similar functions and they should have some common characteristics. The five different categories and corresponding information or properties are shown in Fig. 6. This Figure only represents an overview for all information requirements. More detailed requirements, such as the description of different load types or information on some specific sections is not shown here.

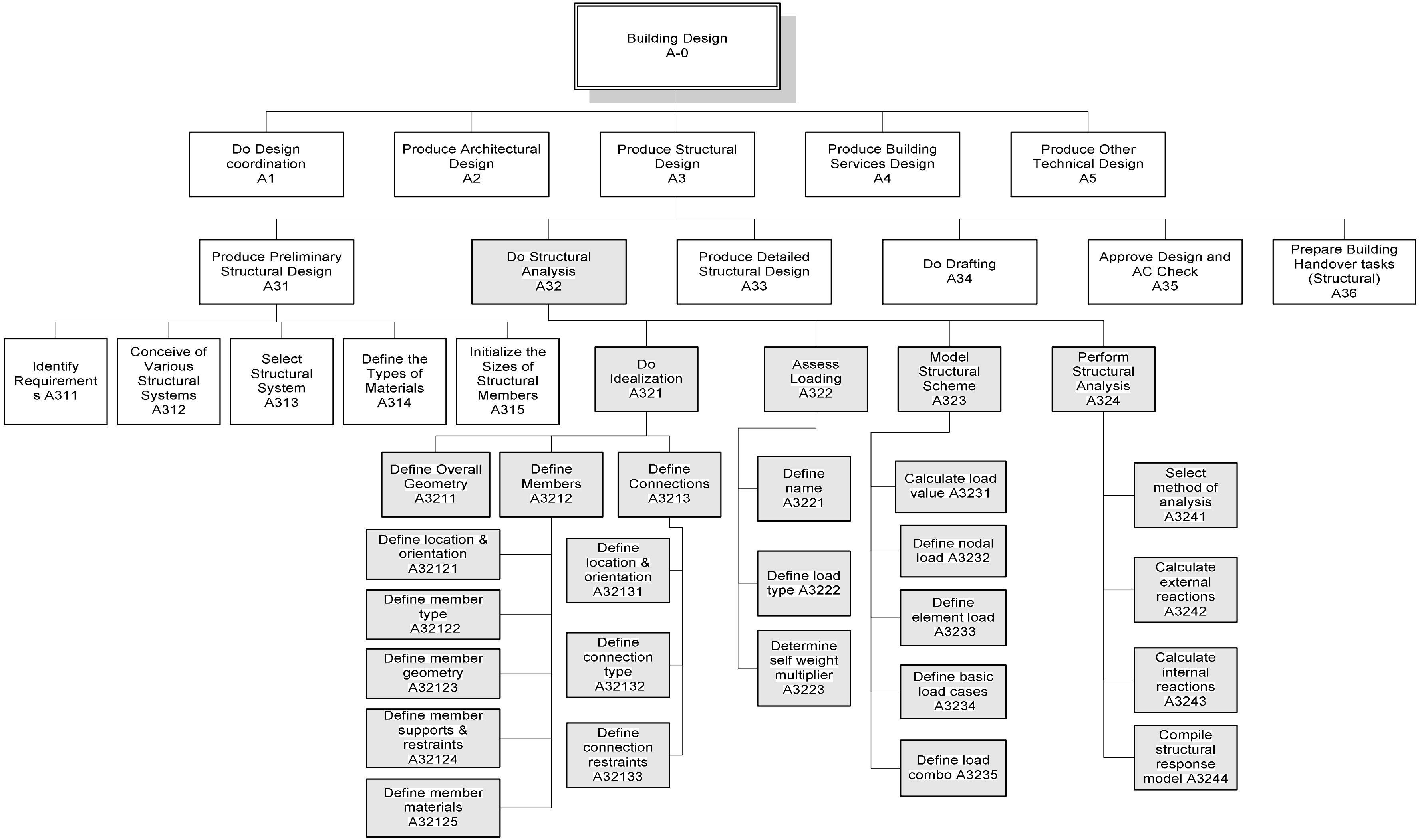


FIG. 5: IDEF0 Node Tree of Structural Design Process

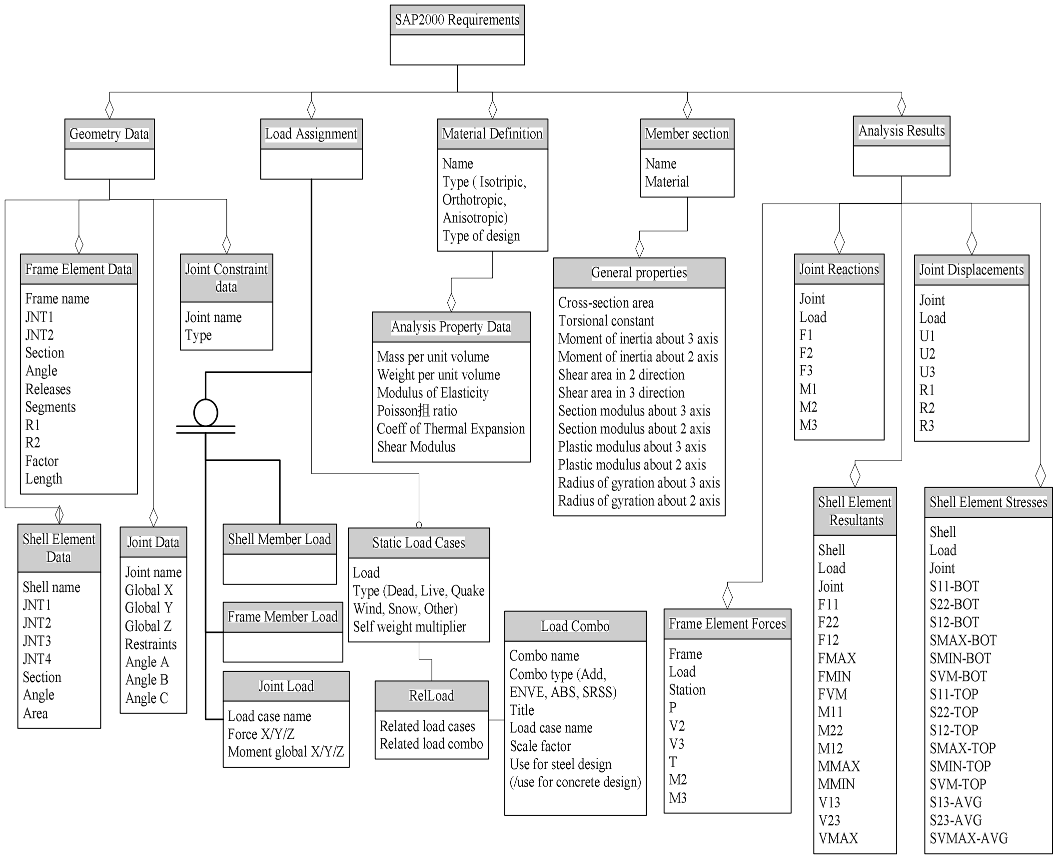
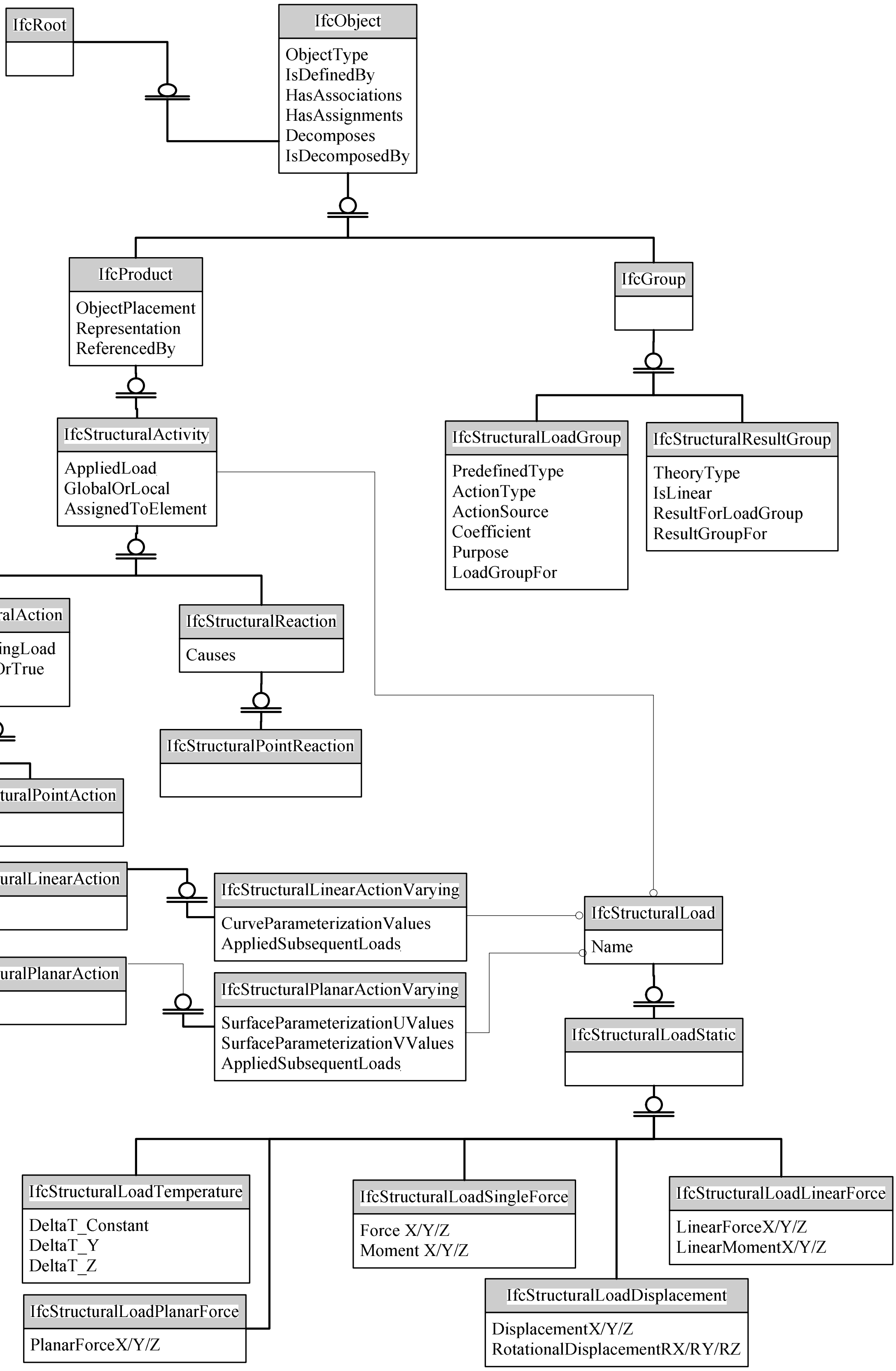


FIG. 6: Information Requirements of SAP2000

4. ASSESSMENT OF THE IFC EXTENSION MODELS FOR STRUCTURAL ANALYSIS

In order to review the capabilities of IFC product models to support structural analysis at multiple levels of detail, comparisons between the information requirements and current IFCs are done. The tasks of comparison include identifying: (1) the definitions already included in the current IFC Release; (2) the definitions which are common between domains; (3) the definitions which are similar between domains; (4) the truly new definitions.

Because of the classifications for information requirements, the comparison also follows these classifications. In next section only the comparison for load information is given as an example. Fig. 7 represents the related current IFC extensions which is included in the release version 2x edition 2 (IAI, 2003), and the comparison is shown in Table 1. Left columns list all the information requirements of SAP2000 to define various load cases, load combinations and load assignment. And right columns enumerate the corresponding IFC definitions and attributes for each information requirement as long as they can be found. Apparently, the blank cells represent the information those don't have corresponding explicit definitions in current IFC Release. They are in different cases. Some is really absent in current models possibly because it is out of scope. Some have their relevant definitions and can be inferred from the existing data. So in blank cell the detailed case for missing information is also described. From this table, we can find that fortunately most of the load information can be explicitly supported by current IFCs. Some are directly defined. Some need to be inferred using the existing data from the IFC model. However, no matter how minor the gaps exist it still indicates that current IFCs still do not capture explicitly and provide a representation for all load information, like types of load combination and some other minor properties. Thereby, the improvements to current IFCs are necessary.



IfcRoot
IfcObject
ObjectType
IsDefinedBy
HasAssociations
HasAssignments
Decomposes
IsDecomposedBy
IfcProduct
ObjectPlacement
Representation
ReferencedBy
IfcGroup
IfcStructuralActivity
AppliedLoad
GlobalOrLocal
AssignedToElement
IfcStructuralLoadGroup
PredefinedType
ActionType
ActionSource
Coefficient
Purpose
LoadGroupFor
IfcStructuralResultGroup
TheoryType
IsLinear
ResultForLoadGroup
ResultGroupFor
IfcStructuralAction
DestabilizingLoad
ProjectedOrTrue
CausedBy
IfcStructuralReaction
Causes
IfcStructuralPointReaction
IfcStructuralPointAction
IfcStructuralLinearAction
IfcStructuralLinearActionVarying
CurveParameterizationValues
AppliedSubsequentLoads
IfcStructuralLoad
Name
IfcStructuralPlanarAction
IfcStructuralPlanarActionVarying
SurfaceParameterizationUValues
SurfaceParameterizationVValues
AppliedSubsequentLoads
IfcStructuralLoadStatic
IfcStructuralLoadTemperature
DeltaT_Constant
DeltaT_Y
DeltaT_Z
IfcStructuralLoadSingleForce
Force X/Y/Z
Moment X/Y/Z
IfcStructuralLoadLinearForce
LinearForceX/Y/Z
LinearMomentX/Y/Z
IfcStructuralLoadPlanarForce
PlanarForceX/Y/Z
IfcStructuralLoadDisplacement
DisplacementX/Y/Z
RotationalDisplacementRX/RY/RZ

TABLE 1: Comparison of Load Information with Current IFC Releases

<table>
<tr><th colspan="4">Software Requirements</th><th colspan="2">IFC extensions</th></tr>
<tr><th colspan="2">Load</th><th>Elements</th><th>Data Type</th><th>Entities</th><th>Attributes</th></tr>
<tr><td colspan="2" rowspan="4">Static Load Cases</td><td>Name</td><td>Text</td><td>IfcStructuralLoadGroup</td><td>IfcGloballyUniqueId</td></tr>
<tr><td rowspan="2">Type (Dead, Live, Quake, Snow, Other)</td><td rowspan="2">Text</td><td>IfcStructuralLoadGroup</td><td>ActionSource</td></tr>
<tr><td colspan="2">IfcActionSourceTypeEnum</td></tr>
<tr><td>Self Weight Multiplier</td><td>No.</td><td>IfcStructuralLoadGroup</td><td>Coefficient</td></tr>
<tr><td colspan="2" rowspan="6">Load Combination</td><td>Combo Name</td><td>Text</td><td>IfcStructuralLoadGroup</td><td>IfcGloballyUniqueId</td></tr>
<tr><td>Combo Type
(SAP2000: ADD, ENVE, ABS, SRSS)</td><td>Text</td><td colspan="2">Absent (because of static analysis)</td></tr>
<tr><td>Title (description of combo)</td><td>Text</td><td>IfcStructuralLoadGroup</td><td>Purpose</td></tr>
<tr><td rowspan="2">Case Name(choose from above defined load cases)</td><td rowspan="2">Text</td><td>IfcStructuralLoadGroup</td><td>IsGroupedBy (IfcRelAssignsToGroup)</td></tr>
<tr><td>IfcStructuralLoadGroup</td><td>PredefinedType</td></tr>
<tr><td>Scale Factor</td><td>No.</td><td>IfcStructuralLoadGroup</td><td>Coefficient</td></tr>
<tr><td rowspan="14">Load Assignment</td><td rowspan="14">Joint Static Load</td><td colspan="2">Joint Force</td><td>IfcStructuralPointAction</td><td>AppliedLoad (IfcStructuralLoad)</td></tr>
<tr><td rowspan="2">1. Load case name</td><td rowspan="2">Text</td><td>IfcStructuralLoadGroup</td><td>IfcGloballyUniqueId</td></tr>
<tr><td>IfcStructuralLoadGroup</td><td>IsGroupedBy (IfcRelAssignsToGroup)</td></tr>
<tr><td>2. Joint name</td><td>Text</td><td>IfcRelConnectsStructuralActivity</td><td>RelatingElement</td></tr>
<tr><td>3. Force X/Y/Z</td><td>No.</td><td>IfcStructuralLoadSingleForce</td><td>Force X/Y/Z</td></tr>
<tr><td>4. Moment Global XX/YY/ZZ</td><td>No.</td><td>IfcStructuralLoadSingleForce</td><td>Moment X/Y/Z</td></tr>
<tr><td colspan="2">Ground Displacement</td><td>IfcStructuralPointAction</td><td>AppliedLoad (IfcStructuralLoad)</td></tr>
<tr><td rowspan="2">1. Load case name</td><td rowspan="2">Text</td><td>IfcStructuralLoadGroup</td><td>IfcGloballyUniqueId</td></tr>
<tr><td>IfcStructuralLoadGroup</td><td>IsGroupedBy (IfcRelAssignsToGroup)</td></tr>
<tr><td>2. Joint name</td><td>Text</td><td>IfcRelConnectsStructuralActivity</td><td>RelatingElement</td></tr>
<tr><td>3. Translation X/Y/Z</td><td>No.</td><td>IfcStructuralLoadDisplacement</td><td>Displacement X/Y/Z</td></tr>
<tr><td>4. Rotation about XX/YY/ZZ</td><td>No.</td><td>IfcStructuralLoadDisplacement</td><td>RotationDisplacement RX/RY/RZ</td></tr>
<tr><td rowspan="5">Load Assignment</td><td rowspan="5">Frame Member Static Load</td><td colspan="4">Gravity load</td></tr>
<tr><td rowspan="2">1. Load case name</td><td rowspan="2">Text</td><td>IfcStructuralLoadGroup</td><td>IfcGloballyUniqueId</td></tr>
<tr><td>IfcStructuralLoadGroup</td><td>IsGroupedBy (IfcRelAssignsToGroup)</td></tr>
<tr><td>2. Frame name</td><td>Text</td><td>IfcRelConnectsStructuralActivity</td><td>RelatingElement</td></tr>
<tr><td>3. Gravity multipliers X/Y/Z</td><td>×</td><td>IfcStructuralLoadGroup</td><td>Coefficient</td></tr>
</table>

<Table1 - continued>

Load Assignment	**Frame Member Static Load**	Point load			
		1. Load case name	Text	IfcStructuralLoadGroup	IfcGloballyUniqueId
				IfcStructuralLoadGroup	IsGroupedBy
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Type	×	**Inferred**	
		4. Direction	Text	IfcStructuralActivity	GlobalOrLocal
				IfcStructuralAction	ProjectedOrTrue
		5. Distance	No.	IfcStructuralPointAction	ObjectPlacement
		6. Load value	No.	IfcStructuralPointAction	AppliedLoad
				IfcStructuralLoadSingleForce	Force/Moment
		Uniform load			
		1. Load case name	Text	IfcStructuralLoadGroup	IfcGloballyUniqueId
				IfcStructuralLoadGroup	IsGroupedBy
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Type	×	**Inferred**	
		4. Direction	Text	IfcStructuralAction	GlobalOrLocal, ProjectedOrTrue
		5. Load value	No.	IfcStructuralLinearAction	AppliedLoad
				IfcStructuralLoadLinearForce	LinearForce/LinearMoment
		Prestress load (*Out of Scope*)			
		1. Load case name	Text	IfcStructuralLoadGroup	IfcGloballyUniqueId
				IfcStructuralLoadGroup	IsGroupedBy
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Scale factor	×	**Out of Scope**	
		Temperature load			
		1. Load case name	Text	IfcStructuralLoadGroup	IfcGloballyUniqueId
				IfcStructuralLoadGroup	IsGroupedBy
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Type	×	= *Temperature* **(Inferred)**	
		4. Temperature	No.	IfcStructuralLoadTemperature	DeltaT_Constant
		5. Pattern (Temp/Pres)	Text	**Absent**	
		6. Multiplier	No.	**Absent**	
		Trapezoidal span load			
		1. Load case name	Text	IfcStructuralLoadGroup	IfcGloballyUniqueId
				IfcStructuralLoadGroup	IsGroupedBy
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Type	×	**Inferred**	
		4. Direction	Text	IfcStructuralActivity	GlobalOrLocal
				IfcStructuralAction	ProjectedOrTrue
		5. Distance	No.	IfcStructuralLinearActionVaring	CurveParameterizationValue
		6. Load value	No.	IfcStructuralLinearActionVaring	AppliedSubsequentLoads

<Table1 - continued>

Load Assignment	Shell Member Static Load	Gravity load			
		1. Load case name	Text	IfcStructuralLoadGroup	IfcGloballyUniqueId
				IfcStructuralLoadGroup	IsGroupedBy (IfcRelAssignsToGroup)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Gravity multipliers X/Y/Z	×	IfcStructuralLoadGroup	Coefficient
		Pressure load			
		1. Load case name	Text	IfcStructuralLoadGroup	IfcGloballyUniqueId
				IfcStructuralLoadGroup	IsGroupedBy (IfcRelAssignsToGroup)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Pressure (by element)	No.	IfcStructuraPlanarActionVaring	AppliedLoads
				IfcStructuralLoadPlanarForce	PlanarForce X/Y/Z
		4. Pressure (by Pattern)	Text	**Absent**	
		4.1. Multiplier	No.	**Absent**	
		Uniform load			
		1. Load case name	Text	IfcStructuralLoadGroup	IfcGloballyUniqueId
				IfcStructuralLoadGroup	IsGroupedBy (IfcRelAssignsToGroup)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Load value	No.	IfcStructuraPlanarAction	AppliedLoads
				IfcStructuralLoadPlanarForce	PlanarForce X/Y/Z
		4. Direction	Select	IfcStructuralActivity	GlobalOrLocal
				IfcStructuralAction	ProjectedOrTrue
		Temperature load			
		1. Load case name	Text	IfcStructuralLoadGroup	IfcGloballyUniqueId
				IfcStructuralLoadGroup	IsGroupedBy (IfcRelAssignsToGroup)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Type(Temperature, Gradient)	×	**Absent**	
		4. Temperature (by element)	No.	IfcStructuralLoadTemperature	DeltaT_Constant
		5.Temperature (by Pattern)	Text	**Absent**	
		5.1. Multiplier	No.	**Absent**	

Similar comparisons are executed to other four sorts of information. Through analysis, we have found that most of the product features and properties shown in Fig. 6 can be found directly or inferred from IFC product models. Only in some minor respects IFCs can not provide sufficient representations. The main initial findings with respect to the suitability of the IFC 2x Edition 2 to support structural analysis processes are as follows:

- For a simple structure, most of the mechanical features and properties necessary for static structural analysis can be found in current IFC Release.
- Some information need be inferred from the data in IFC, such as the “Type” in SAP2000 when assigning static load cases to frame element, its value is either “Force” or “Moment” which can be inferred from the definition of “IfcStructuralLoad” and is not necessary to change current models.

- However, the only items IFC doesn’t support include prestress load, description for stresses and types of load combinations, etc.

Table 2 sums up the overall gaps between all the information requirements of SAP2000 and current IFCs extensions in release 2x Edition 2. Not only the missing information is given, but also they are classified to different scenarios according to IFC 2x Extension Modelling Guide (IAI, 2001). For different scenarios, various approaches will be considered to be adopted for extension development of the IFC Model. The possible approaches are also listed in Table 2. Extension is based on analysis of the gaps exist between the concepts need to be incorporated for the extension model development and the concepts that already form part of the IFC Model. There are three scenarios that may be observed from gaps analysis: (1) concepts exist in the IFC model, (2) concepts extend the IFC model, and (3) new concepts. In different scenario, additional information requirements can be captured in different ways. Of course, all of these problems can be solved by appropriate API programming when implementing. But when some information is a general requirement for all users, improvement for current model will be considered. Therefore it is necessary to perform the generality studies as Section 5.

TABLE 2: Overall Gaps between SAP2000 Requirements and IFC 2X2

	Gaps	**Scenarios for IFC Development**	**Possible Development in Different Ways**	
			Alternative Methods	**Possible Extensions**
Geometry	Location of Elements	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	Derived the absolute displacements from relative displacements
	Length	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	Pset_BeamCommon_Span Derived from IfcReldefinesByProperties or Depth of IfcExtruderAreaSolid
	Restraints of Joint	Concepts exist in the IFC Model	1. Add derived attributes 2. Additional property sets	Pset_StructuralConnectionCommon_Restraints
	Releases of Frame Element	Concepts exist in the IFC Model	1. Add derived attributes 2. Additional property sets	Derived from IfcBoundaryCondition Pset_StructuralMemberCommon (notice the conditions- release combinations which are not permitted)
	Joint Pattern	New Concepts	1. New classes 2. Additional property sets	IfcPattern IfcRelConnectsJointPattern
Load	Distance	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	Derived the direct displacements from relative displacements
	Load Direction	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	Pset_ StructuralActivity
	Prestress Load	Concepts exist in the IFC Model	New class	New class for prestressing cable: IfcPrestressingCablePattern New class as subtype of IfcStructuralLoadStatic
	Type	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	No need to modify the IFC Model, just process and decompose the load data to two parts: force and moment when programming
	Temperature Load	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	No need
	Combo type	Concepts extend the IFC Model	1. Add new attributes 2. Additional property sets	1. new attribute to IfcStructuralLoadGroup; 2. Pset_LoadCombination

<Table2 - continued>

	Gaps	Scenarios for IFC Development	Possible Development in Different Ways	
			Alternative Method	Possible Extensions
Material	Type of Material	Concepts extend the IFC Model	1. New classes 2. Additional property sets	Current stage, no need do more extend for other anisotropic mateiral
Material	Weight Per unit Volume	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	1. new attribute to IfcGeneralMaterialProperties 2. new property sets
Material	Concrete Shear Stress	Concepts exist in the IFC Model	1. New attribute 2. Additional property sets	1. new attribute to IfcMechanicalConcreteMaterialProperties —Shear stress 2. Pset_ConcreteMaterialProperties
Member Section	Radius of Gyration	Concepts exist in IFC Model	1.Additional property sets 2. Implementation agreement	Pset_StructuralProfileProperties
Member Section	Plastic Modulus	Concepts exist in IFC Model	1.Additional property sets 2. Implementation agreement	Pset_StructuralProfileProperties
Member Section	Shape Type	Concepts exist in IFC Model	1.Additional property sets 2. Implementation agreement	No need
Member Section	Material	Concepts exist in IFC Model	1.Additional property sets 2. Implementation agreement	No need
Member Section	Double angle/Double channel –	Concepts extend the IFC Model	1. New attributes/classes 2. Additional property sets	1. New classes: subtypes of IfcCompositeProfileDef 2. Additional property sets Pset_CompositeProfileDefProperties
Member Section	IfcIshapeProfile Def	Concept exist in IFC Model	Maybe need improved definition	(definition is not very clear between asymmetric and symmetric)
Other	Shell Element Principle Forces	Concepts extend the IFC model	1. New attributes/classes 2. Additional property sets	New classes: subtype of *IfcStructuralLoadStatic*
Other	Shell Element Stresses	New concepts	New classes	Subtype of *IfcStructuralLoad*

5. GENERALITY STUDIES FOR INFORMATION GAPS

In some scenario, more than one kind of approaches can be adopted when developing the IFC extensions. Additional information requirements can be captured by adding new classes, supplying additional attributes to existing classes or additional property sets. At this time, which approach is most suitable comes to a problem to the extension developer. Adding new classes or additional attributes to existing classes means a kind of change to the corresponding schema. It is very open-and-shut for end user to understand what information is needed in this domain. But for current works on IFC implementation, this will address the problem to modify current program in order to comply with the new schema. It will impact on exchange files previously generated. Therefore, more difficulties or additional iterative works are unavoidably induced for the on-going or finished IFC-implementation activities. However if all missing information is complemented by the way of defining additional property sets, there is no any influence upon current implementation projects. IFC Property Set provides the capability for dynamic extension. So the principle to IFC extension model development is that unless there is a very good reason otherwise, extension model developments should try to use the same attribute names and definitions as already exist within the IFC model to express the same or a similar idea, and adding new classes are minimized to the best of your abilities. This minimizes conflict and confusion for organizations that will implement the extension model. Accordingly the new question comes to us is that whether this information should be included in the IFCs by amending the schema. We can not have a clear answer to this question only by comparing. Thereby in order to confirm whether it is necessary to add new classes to schema or make any change to current schema, Generality Studies are implemented by investigating other six different structural analysis software in this research. The result of Generality Studies is illustrated in Table 3.

TABLE 3: Generality Studies for Information Gaps

	Gaps	ETABS	SODA	STRAP	REAL3D-Analysis	STAAD pro 2003	PROKON	Genera-lity	Suggested solution w.r.t IFC
Geometry	Location of Elements	v	v	v	v	v	v	Yes	Pset/ Programming
	Length	v	NA	v	v	v	NA	Already have in Pset	Pset (already include)
	Restraints of Joint	v	Support Type (v)	v	v	Support (v)	v	Yes	Pset/ Programming
	Releases of Frame Element	Partial	NA	Both/one end; moment/ shear release	Only has moment release for beam	v	NA	Yes	Pset/ Programming
	Joint Pattern	NA	NA	NA	Prestress is out of scope	NA	NA	No	Programming
Load	Load Direction	v	Global X/Y/Z; Axial; Local X/Y	Load type; FX1/FX2	Coord-sys; Direction	X/Y/Z; GX/GY/GZ; PX/PY/PZ	v	Partly general	Programming
	Prestress Load	NA	NA (steel struc.)	v (same with STAAD)	NA (Out of Scope)	v (Same with STRAP)	NA	Basically Yes	New Classes
	Type	v	Has Force & Couple	Local; Global; Global Projected	Direction: X/Y/Z -> ‘Force’, OX/OY/OZ ->‘Moment’	Assign force and moment respectively	v	No	Programming
	Tempera-ture Load	Uniform Temp. change	Temp. change	Temperature change	NA Out of Scope	Directly definition	Temp. change	Existed	No need change
	Combo type	v	Only additive	Only additive	Only additive	SRSS/ABS	Only additive	Partly	New Attribute
Material	Type of Material	v	NA (For steel frameworks)	Isotropic & Orthotropic	No.	Isotropic & Orthotropic	NA	Yes	Future
	Weight per unit volume	v		v	v	No.(mass density)	No.(mass density)	No	Programming
	Concrete shear stress	No		NA	NA (only do analysis)	NA	No	No	Programming

<Table3 - continued>

	Gaps	ETABS	SODA	STRAP	REAL3D-Analysis	STAAD pro 2003	PROKON	Genera-lity	Suggested solution w.r.t IFC
Member Section	Radius of Gyration	v	NA (fixed database according to steel code)	No	No	No	No	No	Programming
	Plastic Modulus	v		No	No	No	No	No	Programming
	Shape Type	v		No	No	No	No	No	Programming
	Material	v	NA (steel always)	v	v	v	v	Existed	Programming
	Double angle/Double channel –	v	NA	Standard specifications for these kind of shapes	No	NA	NA	No	Programming
Other	Shell element stresses	v	v	±Sx / Sy / Sxy ±Max / Min	Difference: Sxx/yy/zz Sxy/yz/xz	± Sx / Sy /Sxy / Sxz / Syz Max / Min / Max Shear	v	Partly	New class (future)

Note: "v"—the corresponding information is defined in the same way with SAP2000

5.1. Geometry

1. Basically the location of joint or element in all software is defined as absolute global displacement. In this point all are the same. We can consider processing this part of information by programming or attaching them by *IfcRelDefinesByProperties* by an *IfcPropertySet.* Additional property sets don't mean the change to corresponding schema. So to a certain extent, these two ways have the same function.

2. In all software the ways to define the "Restraints" of Joint or "Release" of frame elements are the same. That is to click the check box. If checked, means restrained and vice versa. In SAP2000, the values for this item include "I" (released in "Start" end) / "J" (released in "End")/ "IJ" (released in both ends). In other software, maybe the value is expressed by 0 or 1. No matter what kind of value is used, the primary meaning is the same. For this part of information, there already have definitions in current IFC models. They can be inferred from *IfcBoundaryNodeCondition* for *IfcStructuralConnection* or *IfcRelConnectsStructuralMember.* So this information can be added into current IFC by Pset.

3. For the definition of Joint Pattern, after investigating other six structural analysis and design software, it is found that this concept is specific to SAP2000. It is not a general concept among others. Therefore it is not necessary to give a new class for this concept. It is ok to just handle this during the programming.

5.2. Load

1. In SAP2000, "Distance" represents the location of load applied. It can be derived from the attribute "ObjectPlacement" of entity "*IfcStructuralAction*". Furthermore, this parameter is not necessary to all load cases. So we process it by programming during the implementation.

2. Almost in all software, "Load Direction" includes two parts of information. One is coordination system, local or global. The other is the detailed direction in different axis. The minor difference between different software only lies on different classification or combination of the coordination system and detailed directions.

In SAP2000, there are totally 11 kinds of load direction: Local 1/2/3; Global X/Y/Z; Global X/Y/Z Projected; Gravity; Gravity Projected. The value for it can be from the attributes "GlobalOrLocal" and "ProjectedOrTrue"of *IfcStructuralAction*. The mapping between them is as following table:

TABLE 4: Mapping of Load Directions between SAP2000 and IFC Model

SAP2000	Attributes Values of IfcStructuralAction	Detailed Direction in 3 Axis
Local 1/2/3	GlobalOrLocal: LOCAL_COORDS	Derived from the value of IfcStructuraLoad.
Global X/Y/Z	GlobalOrLocal: GLOBAL_COORDS	
Global X/Y/Z Project	GlobalOrLocal: GLOBAL_COORDS ProjectedOrTrue: PROJECTED_LENGTH	
Gravity	GlobalOrLocal: GLOBAL_COORDS	
Gravity Projects	GlobalOrLocal: GLOBAL_COORDS ProjectedOrTrue: PROJECTED_LENGTH	

Basically all this information is included in current IFC models. So it is not necessary to add new classes or property sets.

3. "Prestress Load" is out of the scope of project ST-4. But the way of SAP2000 to define prestress load is not common between domains. There is no need to add new class for "Frame Prestressing Patten". So further detailed study is needed. Some new classes may be developed directly, such as the subtypes of entity *IfcStructuralLoadStatic.*

4. "Type" can be inferred from the status of value of structural load and the content of *IfcStructuralLoad* need be decomposed to several Load Assignments in SAP2000.

5. Similarly the way of SAP2000 to define Temperature Load by "Joint Pattern" can not represent the general method in other software. The more general way is to define temperature change directly. So from this point of view, the existing definition for temperature load in IFC is sufficient.

6. Combo type: Considering the future use of IFC model, now we can add this new information by attribute to Entity *IfcStructuralLoadGroup*.

5.3. Material

1. In current IFC Release only isotropic materials are allowed for. In future releases also anisotropic materials and their usage may be considered. It means that in future the new attributes or new classes which are subtypes of existing classes *IfcMaterial* are needed.

2. Mass per unit volume and weight per unit volume are related by the value of gravitational acceleration in the current length units (386.4in/s2, 9810mm/s2). So no matter which one is needed by software, only one of them defined is all right. Here there is no necessary to add any new information about this to current IFCs.

3. About concrete shear stress, since most analysis software don't require the definition of concrete shear stress and it can be calculated from existing data, so we can get it during programming.

5.4. Member Section

1. For the information like "Elastic Section Modulus, Radius of Gyration and Plastic Modulus", which can be directly derived or calculated from the basic six attributes of *IfcStructuralProfileProperties*, in other software they all are not necessary to be defined by users. So here this information is just calculated during generating the inputs for SAP2000.

2. Similarly, "Shape Type" is not a general property. It is only a special requirement of SAP2000. Its value is automatically calculated from specified section dimensions. So it is not qualified to add a new attribute for IFC model.

3. For most structural analysis software, when assigning the section to structural member, the property "Material" should be defined. In IFC Model, they are two independent parts which are connected by the common assigned structural member. Anyway this information can be found in current IFC models.

4. For special sections, most can be found corresponding special IFC definitions for them. Just only for “Double Angle” or “Double Channel”, the properties “Outside width” and “Back to back distance” need be calculated. In some software, there are standard specifications for these kinds of shapes. The “Outside width” or “Back to back distance” is also provided standard. So we just calculate the value for them when processing the data according to the equations.

5.5. Other Information

Shell element stresses are out of scope in the current IFC model, therefore a new class will obviously be needed in a future extension of the model.

6. RECOMMENDATIONS FOR FURTHER DEVELOPMENT OF THE IFC EXTENSION MODEL FOR STRUCTURAL ANALYSIS

The above section’s discussion for information is all from software viewpoint. From an Information Technology viewpoint, the extension developments of these information gaps are as follows:

1. Expression of Restraints of Joint or Release of Member through Use of Property Sets

Refer to the different scenarios, for concepts existed in the IFC model, viz. restraints information of joints or release information of frame members, property sets are used for adding this information to existing IFC structural items. This approach has the advantage of coexistence with other domain’s schemas. Fig. 8 shows the expression of structural items in IFC and the relationship with the extension.

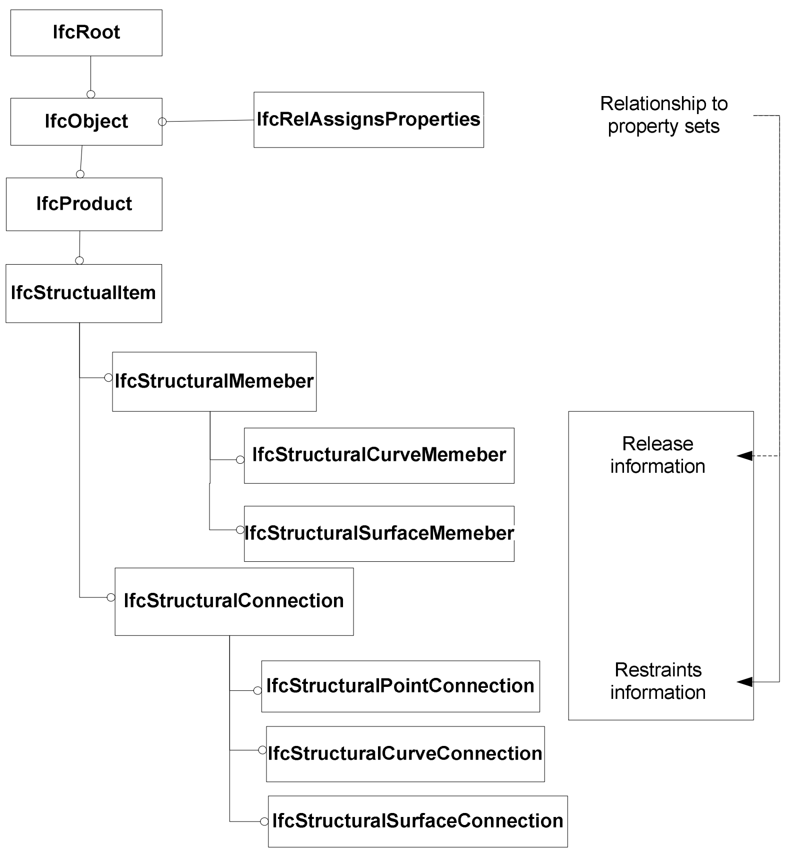


FIG.8: Expressions of Structural Items in IFC

2. New classes for Prestress Load

Prestress Load is out of the scope of project ST-4. For a certainty there is no any definition for it in current IFC models. Undoubtedly it belongs to new concepts. Generally for new concepts new classes need to be specified that get support from the fundamental ideas within the resource layer and the core layer. Although our principle is to minimize the required new class as possible as I can, this time new class is required to extending the IFC load resource.

In SAP2000, the precondition for defining “Prestress Load” is to define the “Frame Prestressing Pattern” which is the pattern of prestressing cable. Each cable is subject to the following specifications: (1) cable tension; (2) cable eccentricities (Start, Middle, and End). Each prestressing cable produces a set of self-equilibrating forces and moments that are proportional to the cable tension, such as tensile forces acting on joints and the moments acting on joints that are proportional to the drapes respectively, etc. The sum of these forces and moments for all prestressing cables acting on a frame element form the unscaled prestress load for that element.

In a word, defining prestress load is a very complex work. Only one simple new class may be not enough to express it accurately. Thus this part will be left for further study.

3. Combo Types & Types of Material

Dynamic analysis is also out of the scope of project ST-4. Therefore, in current IFC models, the type of load combination is always set as additive by default (where the value is “ADD” in SAP2000). The other three types are ENVE, ABS and SRSS. ENVE is used for moving loads and any analysis case where the load producing the maximum or minimum force/stress is required. ABS and SRSS are used for lateral loads. For the type of material, in this IFC Release only isotropic materials are allowed for. Both the combo types and material types belong to the second scenario, concepts extend the IFC model. That is, they need extension to fully capture additional information requirements. In future releases also anisotropic materials and their usage, as well as other combination methods for structural analysis cases may be considered. In that case, some data types or new attributes to existing classes are needed. Fig. 9 illustrates the new attribute added to class *IfcMaterial* for describing the material types.

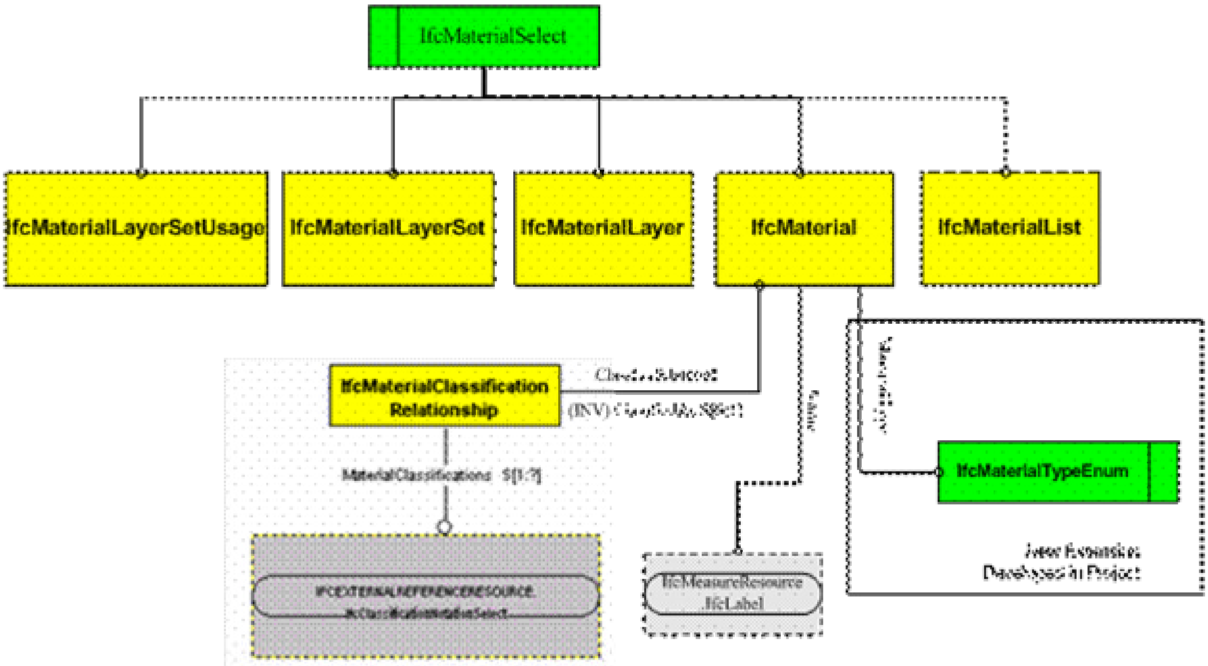


FIG. 9: Expression of “Type of Material” by New Attribute

4. Expression of Principal Forces & Moments for Shell Elements

Similarly, the new class is added as a subtype of *IFcStructuralLoadStatic* to express the principal forces and moments.

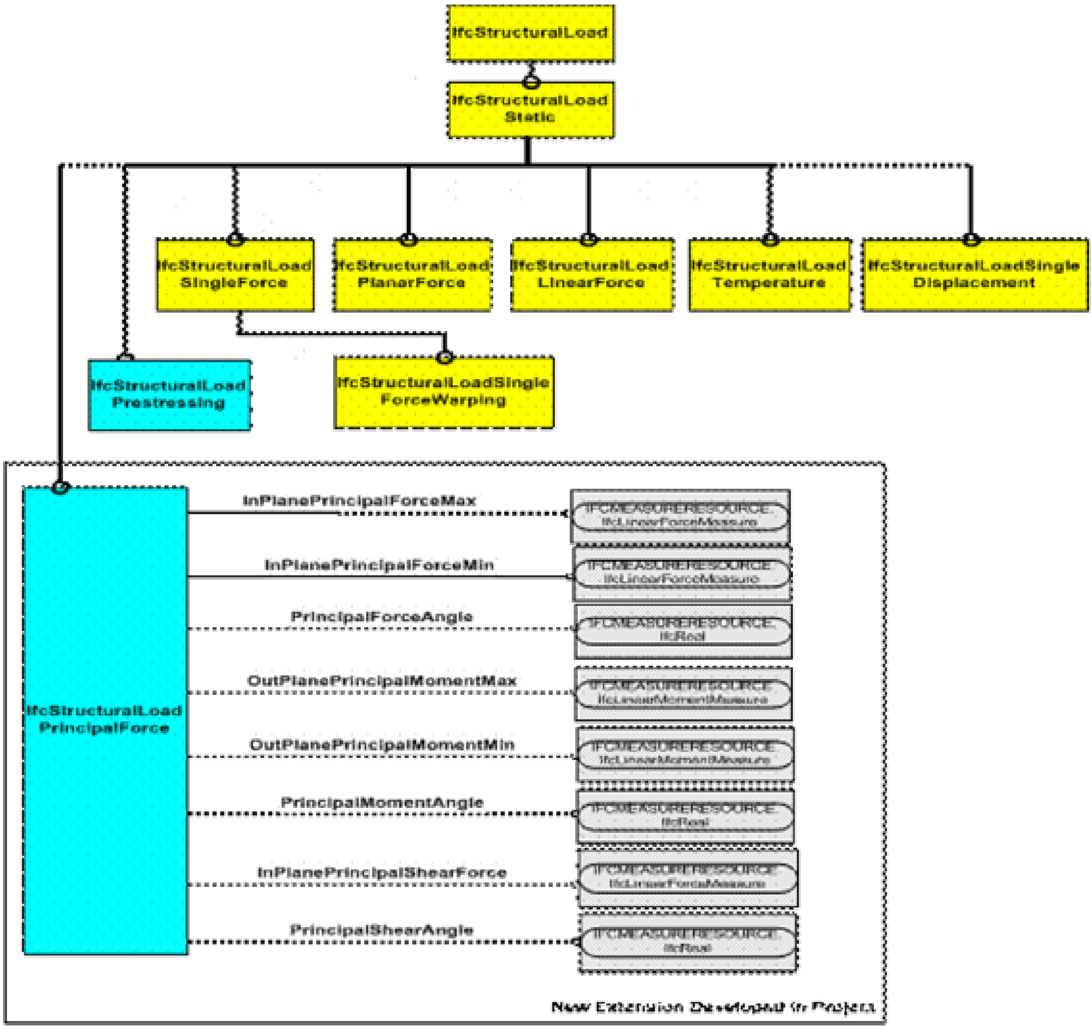


FIG. 10: New Class for Principal Forces & Moments for Shell Elements

7. CONCLUSIONS

In order to implement the integration between architectural design and structural analysis successfully, the information requirements of SAP2000 from software point of view are analyzed in this paper. The capabilities of IFC product models to support structural analysis are assessed. After comparing the information requirements with current IFC models, it can be found that most of information needed by SAP2000 to do structural analysis can be explicitly supported by current IFCs. Some have their corresponding definitions directly in IFCs. Some need inference using the existing data from the IFC model. However, IFCs still do not capture explicitly and provide a representation for some information, such as prestress load and types of load combination etc., which means that some improvement to current IFCs may be necessary. In order to confirm whether it is necessary to change current IFC model, Generality Studies are implemented by investigating other six different general structural analysis software in this research. Accordingly, the commonality of missing information can be verified which make these gaps are not limited to SAP2000 anymore and become a kind of "common missing" for structural analysis from general applications' point. Subsequently the appropriate extension approach is selected and some suggestions on IFC extensions development for these information gaps are proposed in the paper. Of course, they just represent some problems which may exist between different definitions of software and IFC models during the implementation activities. And these requests will have a little influence to the current release of IFC. Therefore to some extent, they are only some recommendations which need IAI members have a further review.

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