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TEKLA STRUCTURES IN A STRUCTURAL BUILDING INFORMATION MODELING WORKFLOW

by

Allan Ho

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Professor Cosmas Tzavelis
Advisor

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THE COOPER UNION FOR THE ADVANCEMENT OF SCIENCE AND ART

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Dean Simon Ben-Avi, School of Engineering – January 23rd, 2012

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ABSTRACT

This dissertation is an effort to enumerate a typical workflow involving the use of the computer program 'Tekla Structures' in a Building Information Modeling (**BIM**) strategy as a professional structural engineer. Focus will be given to the coordination with architectural or mechanical models, and structural detailing. The majority of this paper will detail the advantages as well as shortcomings of using Tekla in combination with structural analysis and design software and application programming interface.

TABLE OF CONTENTS

Acknowledgment 3

Abstract 4

Table of Contents 5

List of Figures 7

Table of Nomenclature 9

Building Information Modeling (BIM) 10

Principles of BIM 10

BIM For Structural Engineers 13

Tekla Structures In BIM 22

Structural Engineer Workflow 26

Part I. Modeling 26

Principles of Modeling 26

Import of Information 28

Management of Data Revisions and Changes 33

Data Conversions to Tekla Elements 36

Clash Detection Between Multiple Models 42

Part II. Structural Analysis and Design 45

Structural Analysis in a BIM Workflow 45

Structural Analysis & Design Step By Step Procedure 49

Export to SAP2000 58

Part III. Details and Drafting 62

Connection Design by Excel 62

Overall Structural Engineer's BIM Procedure 69

Conclusions and Recommendations 74

Appendices 76

Appendix A – Software 76

Bibliography 77

LIST OF FIGURES

Figure 1 – Tekla & Revit Workflow. © Tekla. 22

Figure 2 - Tekla BIMSight screenshot 23

Figure 3 - Element Properties & Attributes 27

Figure 4 - Reference Model Properties 32

Figure 5 - Reference Model - Change Management Showing Changed Elements 33

Figure 6 - IFCChangeManagement - Filter Parameters 35

Figure 7 - Grid Dialog Box 38

Figure 8 - IFC Converter tool – Dimensional Tolerances and Mapping 40

Figure 9 - IFC Convert Report 41

Figure 10 – IFC Element - Inquire 41

Figure 11 - Clash Check Manager Dialog Box 42

Figure 12 - Analysis & Design Dialog Box 49

Figure 13 - Analysis Model Properties 50

Figure 14 - Analysis Model – Output 51

Figure 15 - Analysis Model Options - Design – Steel 52

Figure 16 - Load Groups Dialog Box 53

Figure 17 - Load Combination Generation 54

Figure 18 – Slab Analysis Properties Dialog Box 55

Figure 19 - Slab Analysis Properties - Loading Tab 55

Figure 20 – Slab Analysis Properties - Position Tab 56

Figure 21 – Overview Analysis Model 57

Figure 22 - Analysis Application Interface - Export to A&D Software 58

Figure 23 - Tekla Analysis Model Exported to SAP2000 59

Figure 24 – Analysis Export List 60

Figure 25 - Tekla Connections 64

Figure 26 - Component 141 - Inputs Sheet 65

Figure 27 - InsertProperties.xls - For Attribute Mapping 66

Figure 28 - Component 141 - Outputs Sheet 67

Figure 29 - Component 141 - Excel Calculation Sheet 68

TABLE OF NOMENCLATURE

2D	Two-Dimensional
3D	Three-Dimensional
ACI	American Concrete Institute
AEC	Architecture-Engineering-Construction
AIA	American Institute of Architects
AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
API	Application Programming Interface
ASTM	American Society for Testing and Materials
A&D	Analysis and Design
BIM	Building Information Model or Building Information Modeling
BOMA	Building Owners and Managers Associations
CAD	Computer Aided Drafting
CIFE	Center for Integrated Facility Engineering
HVAC	Heating, Ventilation, and Air Conditioning
IAI	International Alliance for Interoperability
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
MEP	Mechanical, Electrical, and Plumbing
NIBS	National Institute of Building Sciences
NIST	National Institute of Standards and Technology
PCI	Precast/Prestressed Concrete Institute

BUILDING INFORMATION MODELING (BIM)

PRINCIPLES OF BIM

BIM is the virtual simulation of the entire construction project's life cycle through an object-oriented digital database. An example of BIM is the usage of computer programs that have the ability to communicate to each other either through application programing interface (API) or through compatible file formats. The example of BIM that will be used as a popular example throughout the thesis is the architect using Autodesk Revit Architecture to develop the concept and working design, the structural engineer using Tekla in conjunction with the SAP2000 analysis and design software, the MEP engineers using Revit MEP, the tenant/owner using Tekla BIMSight to ask questions and communicate with the professionals, and the contractor using his/her own IFC-compatible construction management software (possibly Tekla's new construction management module). A project-team accessible central server is of vital importance to the successful implementation of BIM as BIM can be any number of different software communicating with each other but the quick and easy access to information is the main focus.

The design and construction of a building is not a simple, linear process. It is a complex collaboration of a full spectrum of fields: architecture, engineering (structural, mechanical, electrical, plumbing), construction management, general contracting, finance, and business. Both in the design and construction phases, there are tasks that are mutually dependent – a delay in a single task could potentially cause multiple, costly rescheduling. Compounding postponements cost money in various ways, including equipment rental costs, cancelled-labor fees, and foregone lease revenue. One major cause of delays in the architectural, engineering, and construction (AEC) industry is time required for collaboration between the trades. The well-known adage of measuring twice and cutting once applies to construction as well. The cost of troubleshooting during design is trivial compared to the extra expense of redesigning during construction. A benefit of building information modeling is the fact that all participating trades will have access to the full database of information, allowing troubleshooting and conflict resolution to occur during design.

Information is shared with every party, reducing redundancy in information/model duplication as well as decreasing the need to request additional information for coordination. However, this information is no substitute for the judgment and critical thinking of a professional, but exists as a supplement to assist them. BIM is not a black-box solution that generates answers for architects or engineers. It is, however, very important to note that "Unlike [Computer-Aided Drawing Design] CADD, which primarily automates aspects of traditional drawing production, BIM is a paradigm change." (Eastman, 149) BIM's lies in its ability to "redistribute the distribution of effort." (Eastman, 149) While BIM does not change the responsibilities and goals of the professional, it does change the modus operandi. Some procedures generally associated with the construction phase of the project are going to shift to the design phase. The shift of project scope undoubtedly equates to a shift in the project cost breakdown from construction to design. Whether or not the industry is going to resist this type of shift in responsibilities, and revenue, is yet to be seen. The politics and analysis of the financial repercussions of BIM is beyond the scope of this thesis and shall be noted as a topic worthy of further exploration.

BIM has an enormous potential to increase the quality of the architecture, engineering, and construction industries while simultaneously decreasing costs provided its strengths are attentively utilized while its limitations acknowledged.

BIM For Structural Engineers

To the AEC industry, BIM is seen as not only useful, but a necessary next step in the evolution of the design and documentation of structures. Buildings are becoming increasingly complex and thus the need to maximize efficiency is an ever-present requirement. Building information modeling has benefits throughout the entire design process from the earliest concepts to building management after construction completion.

BIM has particular uses in complex geometric situations (e.g. a sweeping, undulating façade) as well as intricate building situations (e.g. a structural retrofit of a historical landmark building in a busy location such as midtown Manhattan). The interweaving of increasingly complex architectural, structural, mechanical, and electrical systems makes it more and more difficult to efficiently construct structures. Building information modeling is poised to be the answer to these difficulties as they allow the transfer of databases of information between trades and full leverage of technical advantages of digital data. BIM will be the cumulative acquisition of all information associated with the project. Furthermore, project members will have access to this information in real-time, which mean that any changes made during design or construction can be seen and resolved quickly. BIM is not simply three-dimensional modeling; BIM is the entire database of 'elements' or 'components' that have a plethora of information tagged to each element. In theory, there should never be mistakes such as "The structural engineer had these beams labeled as a A50 Grade W14x22 in their structural drawings but the contractor misread these beams and labeled them as a A36 W12x22 in their steel shop drawings" because all trades will generate their drawings from essentially the same database of information. This should help to prevent inter-trade inconsistencies by eliminating human interpretation errors from data reproduction.

Currently, information created during the design and construction of structures includes multiple redundant duplications. Geometric information from the architect is duplicated by the engineer, contractor, and sub-contractors separately. Aside from inter-trade redundancies, there are also internal redundancies within each trade. An example of which is the creation of two models by the structural engineer – one for detailing and one for structural analysis/design. BIM should help to reduce repetitive work such as updating two models for each structural change made during the design process. That is <u>not</u> to say that the engineer should allow this automation of repetitive tasks to absolve them of professional responsibilities. A change in the structural analysis model that is blindly transferred to the detailing model which causes constructability issues is inexcusable - BIM cannot be used as a justification for mistakes or failings by the structural engineer. Each decision still requires professional analysis and thought – the roles of the structural engineer remain the same but the method of visualization and presentation are upgraded.

BIM advantages are not limited to only the architects, engineers, or construction contractors; even people without professional training can benefit from the organization of a large amount of information in an easy-to-view three-dimensional model. BIM also offers a great amount of value for the client, owner and facility managers. Individuals who are not trained in interpreting architectural or engineering drawings now have the capability to examine mockups of buildings or partial systems to provide functional input during design and construction. After the completion of construction, facility managers and owners also have a representative model with traceable (i.e. RFID chips) information on components. It is a database arrangement of all the information available in a 3D as-built model of the building. This makes maintenance, equipment repair and addition, and feasibility studies cheaper and swifter to complete. It also allows unprecedented organization for building managers, which is important for future structural changes.

To allow different professions to use BIM together, the data must be manipulated into a useful format. BIM allows interoperability between industries one of three ways (Gayer, 2009): direct native file, program Application Programming Interface (API), and open format data exchange. 'Direct native file' is using a program that can open other models in native file format such as Autodesk's Revit Architecture, Revit Structure, and Revit MEP programs. The program must be able to open the files natively without need to convert/interpret database information, which usually ensures lossless data sharing. Program APIs are direct program links that interface a model into other various computer programs such as the link between Autodesk's Revit and Bentley's RAM Structural System. The link uses a series of programming routines that essentially works as a bidirectional translator between programs. The links must be proprietarily developed, which means each combination of programs requires its own dedicated API. Tekla Open API™ is written using Microsoft .NET technology which allows COM and .NET compatible programs (Tekla Basic Concepts, 2011) to accept data from Tekla, run calculations, and then return output to Tekla (i.e. Excel, MS Access, Word, and MathCAD). It also allows users or companies to write applications to enhance the functionality of Tekla. Tekla supports open development of user applications – the Tekla Extranet is a forum and server for the development and distribution of such applications. The third interoperability method is the usage of 'open file formats' such as the Industry Foundation Classes (IFC). This method allows multiple programs to share information without data loss with open source languages (i.e. IFC, CIM/2, or DXF). This concept is essentially the same as 'direct native file' except that it is an open-source industry driven format as opposed to a proprietarily developed format.

At this time, there is no comprehensive BIM program that can effectively model architectural, structural, and mechanical systems together while supporting the individual needs of each profession. This makes the use of the 'direct native file' method difficult when multiple consultants work and design using their own preferred software. It is rare that one vendor can provide a program that satisfies all the requirements in this highly specialized AEC industry. While 'direct native file' is the most efficient form of interoperability, it requires a good amount of initial investment in software design to be properly implemented. When using 'open formats' for interoperability, individual programs must be able to import and export information without data loss so that every party can fully utilize the advantages of the BIM strategy. The most popular open format data exchange today is IFC, a neutral object-oriented file format. Because the IFC format was developed as an open specification that is not controlled by vendors, it facilitates interoperability between software programs. This helps prevent vendors from influencing the BIM workflow and allowing a more industry-driven approach, capitalizing on decades of expertise, experience and specialization. The industry has shown its support for developing IFC as the universal BIM filetype by way of sponsorship from the main industry committees such as American Institute of Steel Construction (AISC), American Concrete Industry

(ACI), and Precast/Prestressed Concrete Institute (PCI). Tekla has also pledged its dedication to the IFC filetype and hailed it as the future of BIM.

Currently, many large architectural companies such as Gensler and Hellmuth, Obata, + Kassabaum (HOK) have begun a of company-wide adoption of BIM programs in lieu of traditional CADD. Autodesk's Revit Architecture computer program is a popular choice for many firms. For structural engineers, more than one single program must be used because drafting and structural analysis are two separate but dependent processes. The analytical model is the simplified representative version of the drafting model. Traditionally, changes made to one model must be coordinated through collaboration between the drafters and the engineers. Using a program with a link between the data used by the drafting and engineering departments can increase efficiency of this collaboration. The parametric data stored in the Tekla database may be leveraged for use to design connections or other details by using Tekla’s design by Excel for components. The final step in the structural engineer’s role in the BIM workflow is to finalize the design of the structural connections and all details necessary for the construction documents. Once analysis and design is complete, construction documents must be produced for both project construction and filing with the appropriate government agencies. Paper construction drawings are still necessary at this point because of its ease of use and durability on construction sites. They are also necessary for permitting and city/state filing because there is no set standard for file formats nor is there presently a widespread acceptance in the industry. While the technology is being improved, legacy problems (backwards compatibility in software) prevent digital documentation for record-keeping.

To summarize, BIM has the potential for these major benefits:

1. Assists in the construction of structures with complex geometries by using three dimensional modeling capable of panning, rotating, layer/element isolation, and generation of sections and elevations.
2. Allows enhanced analysis and design options by linking modeling software with analysis software as well as calculation APIs. Allows automation of designing similar components or systems.
3. Reduces repetitive work such as labeling parts or designing similar components by allowing information tagging and parametric design with API programming (.NET integration).
4. Reduces redundant manual information transfer (e.g. recreating framing plans or project geometry data). Shares data/information with participating parties and allows multiple-user input/output to a shared central hub.
5. Reduces RFI's and coordination during construction by allowing inter-trade 'collision detection' or 'interference detection' between multiple models during the pre-construction and design phases.
6. Decreases construction portion of project schedule by shifting coordination to the design phase as well as allowing earlier identification of construction issues to resolve during the pre-construction phase. The construction portion

is the most costly in terms of delays and is also the most complicated in terms of scheduling. Streamlining construction means reduced cost and a higher quality end product.

7. Provides a wealth of information for building managers and maintenance by producing an indexed database of information of the entire building upon project delivery.

TEKLA STRUCTURES IN BIM

Tekla Structures is a BIM modeling program with origins in steel fabrication and detailing. Tekla uses both program API and open-format exchange through the IFC data format. It has API software links to multiple structural analysis programs (STAAD, SAP2000, Robot Millennium, and Microsoft Excel) as well as with architectural programs (i.e. AutoCAD, ArchiCAD). Tekla also supports importing/exporting or inserting of reference models in several open formats (including dxf, ascii, fem, cimsteel, fabtrol xml, ifc, ifczip, ifcxml, 3dd, dgn, igs, and iges). Tekla has chosen to commit to the open source filetype IFC.

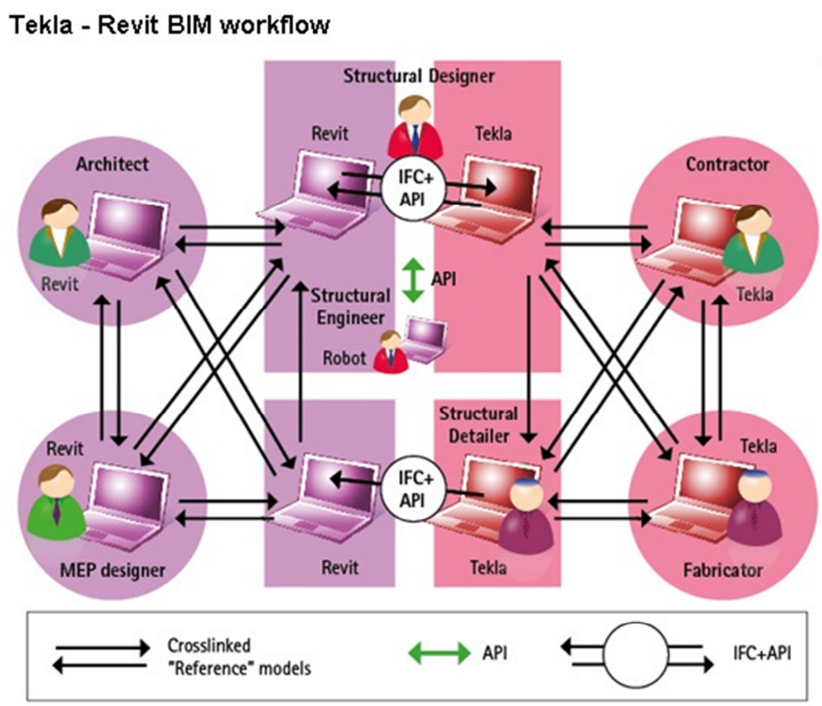

Figure 1 – Tekla & Revit Workflow. © Tekla.

Tekla has also released a free BIM viewer called BIMsight. BIMsight allows parties without the Tekla program to view IFC files in 3D as well as see identification data associated with elements in the model. For instance, a building owner can take a Tekla model of the project and query items such as beam sizes or materials. As seen in Figure 2 below, BIMSight is viewer program that has many features to allow read-only access to many aspects of the project. More importantly, it allows project members without architectural or engineering training to easily measure distances and place notes on three-dimensional objects. This allows an easier way to communicate spatial location as well as a method to visualize the project without complex interpretation. BIMSight allows measurements in metric or imperial units, simple markups using a simple digital pen tool, and notes that can be attached to views/elements.

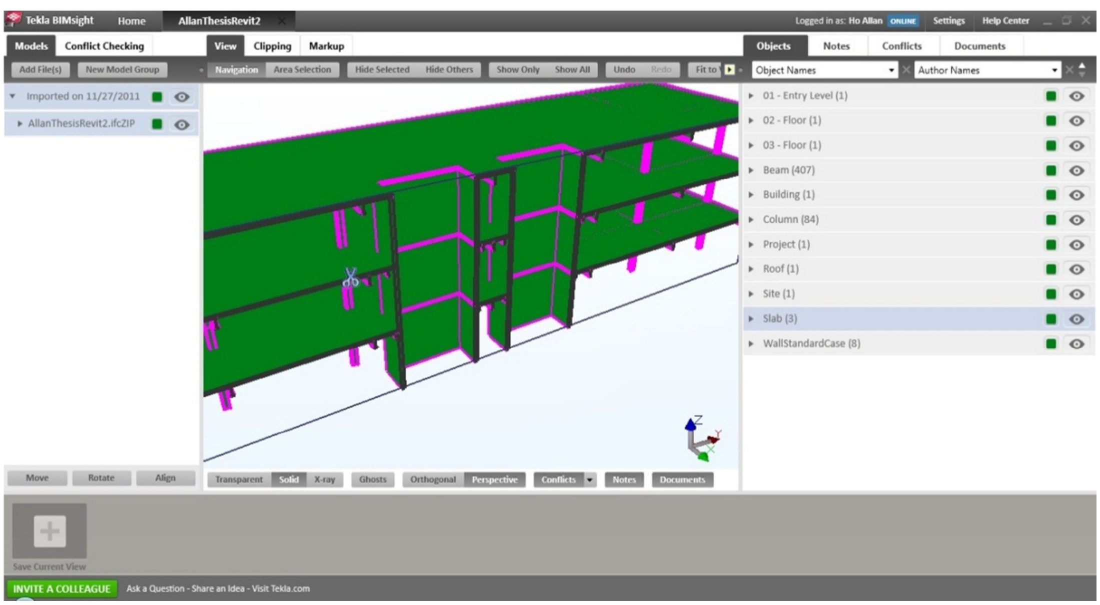

Figure 2 - Tekla BIMSight screenshot

A more powerful aspect of BIMsight is the conflict checking that allows multiple models to be added and cross-checked for interferences. This allows more people to join the design process and contribute. This also shows a commitment on Tekla's part to diversifying the user base of the BIM model, and incorporating more of the AEC industry as a whole to join the process and interact with each other. Another important feature is the ability to leave notes attached to specific views and allowing clipping planes. Thus anyone can look at each consultant's model, manipulate them to see certain areas, and ask questions or make comments without having to own the specific BIM software or need to describe the location of each area of interest. The main focus of the BIMSight program is to make communication much easier between trades without expensive proprietary software.

Even more recently, Tekla released a Construction Management add-on module for its Tekla Structures program which allows any program configuration to use the Construction Management tools such as the scheduler, material take-off generator, and 4D visualization. Since Tekla is a database of element sizes, connections, materials, it would have the data to create detailed weight, quantity, and fabrication information necessary for many scheduling tasks. This module allows the building to be essentially constructed in the program as it would be in real life, allowing scheduling-specific conflict resolution to take place. This analysis can be performed while design work is still being completed to give the construction manager a good grasp on the logistics of the project and help to

All these programs, modules and workflows are leveraging the power of digital model data that is organized. One of the many benefits of using Tekla to model is the ability to have multiple users working on one central file. This thesis will now focus on Tekla's function as a component of BIM for a structural engineer.

STRUCTURAL ENGINEER WORKFLOW

PART I. MODELING

Principles of Modeling

There are three phases of design – schematic design, design development, and construction documentation. A good BIM strategy maintains the data throughout the entire process and eliminates inefficiencies by reducing as much redundant work as possible.

In schematic design, the basic mass and envelope of the building is decided and details such as the main gravity and lateral resistive systems and basic beam and column layouts are fleshed out. For structural engineers, BIM allows the engineer to leverage the architect's work for their own purposes. The advantage of digital data is the ability to isolate relevant information and minimize interpretation. Instead of wondering what the subtleties of linetypes or thickness in 2D lines represent, a plethora of data can be associated with every single line. The manufacturer, material type, finishes, RFID tracking number, and even brief notes can be attached to model elements to keep data organized in an easily searchable and functional format. In Figure 3 , it can be noted that individual elements may have as detailed a set of notes as needed; RFI's regarding elements can be tracked as well as detailed design, detailing, fabrication, and erection data.

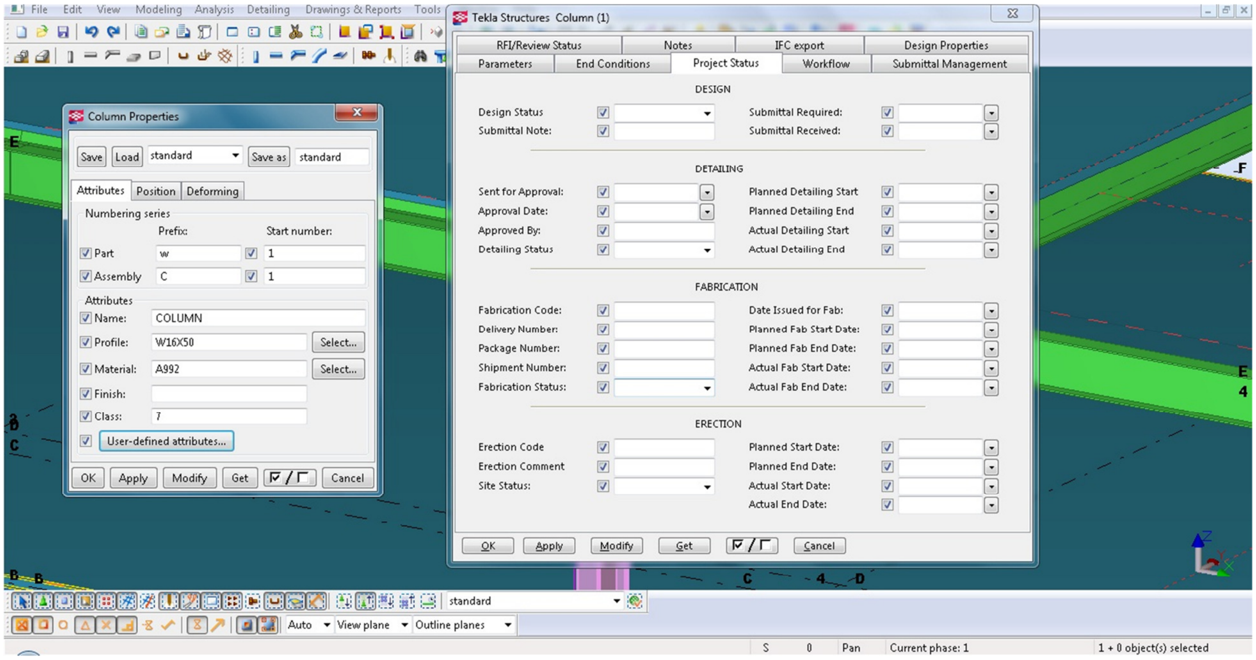

Figure 3 - Element Properties & Attributes

In a way, BIM and Tekla are actively unifying and standardizing the project workflow process. 'Requests For Information' (RFIs) will be centrally located with the project model and drawings instead of spread out in emails and hardcopy prints. This makes tracking through the project in case of legal/contract issues less complicated and more organized.

Currently, the structural engineer must create his or her own structural models from 2D CADD or paper drawings. This transfer of information is full of opportunities for misinterpretation. The process is also a redundant one as the architect has already created most of the relevant geometries. Even more coordination is required when the architect makes inevitable revisions to their model as the project advances. The structural engineer must either spot the changes themselves or rely on the architect to communicate the changes. Relying on other parties for information in this context is risky as no one can assume others to have a professional-level understanding of concepts outside of their own expertise. Architects do not necessarily know how a seemingly innocuous architectural change could have profound structural impacts and structural engineers do not necessarily know how structural changes may throw entire architectural systems awry.

Import of Information

The first step to working with Tekla in a BIM workflow is to import the information available from the architect and sub-consultants. Getting this information to a useful form is an essential part of BIM.

Tekla uses 'reference models' as the digital analogy of creating structural elements using architectural or mechanical drawings as a reference point for dimensions and general building construction/composition. The project is in the schematic design phase at this point. Approximate column locations, level elevations, building footprint and mass, and the building's gravity and lateral systems are being determined. The architect sends the structural engineer preliminary information in one of three ways: paper hardcopy drawings, AutoCAD drawings, or a BIM model (i.e. Revit model with the basic 3D layout of the building). With Tekla's reference model system, changes, additions, and deletions will be a matter of letting the program cross-reference the current architecture model with the older one and displaying the changes automatically. More often than not, the architect requires structural answers during the initial concept phase. They provide architectural drawings that are constantly changing as the project evolves. A lot of coordination effort is wasted as structural engineers have to find the changes and then incorporate them into both the analysis models/calculations and the drafting that has likely started. The structural engineer can now use this information as a reference to begin modeling the structural system for the building.

1.) *Option 1 Non-BIM:* Paper hard-copy architectural drawings are used for manual reference. Begin the model in Tekla starting with Tekla Column Grids.

2.) *Option 2 BIM-Hybrid:* Import AutoCAD files as reference files. AutoCAD lines are converted into useable Tekla lines.

3.) *Option 3 BIM:* Import Revit files as a reference model. Convert IFC objects into Tekla objects with the IFCConverter tool in Tekla.

Option 1 uses no BIM and offers no way to quickly track changes. Manual updating for architectural changes is required. Using Tekla still allows users to use BIM in their portion of the project workflow between detailing and structural analysis. All of the geometric data produced by the architect must be reproduced by the structural engineer – this is wasted manpower and an inefficient means of transferring information.

Option 2, the AutoCAD import is a hybrid workflow. With 2D AutoCAD drawings, there is less information transferred as everything is only representative lines and there is no individual object information. Two-dimensional CAD drawings may be imported and arranged in three dimensions in Tekla. This means that you can place plans at their actual elevation and place elevation drawings wherever they apply. Essentially, the 2D drawings are 'slices' of the building that may be placed exactly where they were 'sliced'. The lines of the AutoCAD are automatically converted to Tekla lines for ease of model creation. 3D CAD drawings may also be imported but in both cases, there is no other information other than geometric and spatial. Extrapolating from the current trend of the industry, there will be a transition period where project teams consist of BIM participants and non-BIM participants. This option is still inadequate to maintain high efficiency levels. This method still allows digital manipulation of data as well as automatic detection of changes.

Option 3, the Revit model import is the BIM workflow. At this point, there is no direct link from Revit to Tekla, which means that the architectural model must be exported as a compatible file format such as IFC. The intermediate step of conversion of

Revit to IFC objects still loses information and is not perfect, but it still retains much of the geometric spatial information and material specifications. Gridlines are also not imported, which must be circumvented by importing an AutoCAD drawing with gridlines (presumably a CAD drawing derived from the Revit model to ensure accuracy). A true BIM workflow allows seamless integration between all models of all trades. From here on, the thesis will focus on Option 3, the Building Information Modeling strategy of using Tekla Structures for structural engineers.

Tekla does not import Revit files (*.rvt) as reference models – the best format to use for interoperability with Revit is the IFC format. For the Revit model import, the architect must use the *Export to Tekla* tool in the Revit program (alternatively, a generic export to IFC model may be selected). This creates an IFCzip file that may be imported into Tekla as a reference model. Import the IFC file by using ***File>>Insert Reference Model****...*

This opens the *Reference Model Properties* dialog box (Figure 4) where the *Layers* option allows the hiding of non-essential layers. For the structural engineer, this allows the isolation of the structurally pertinent members such as the floor, walls, columns, and openings.

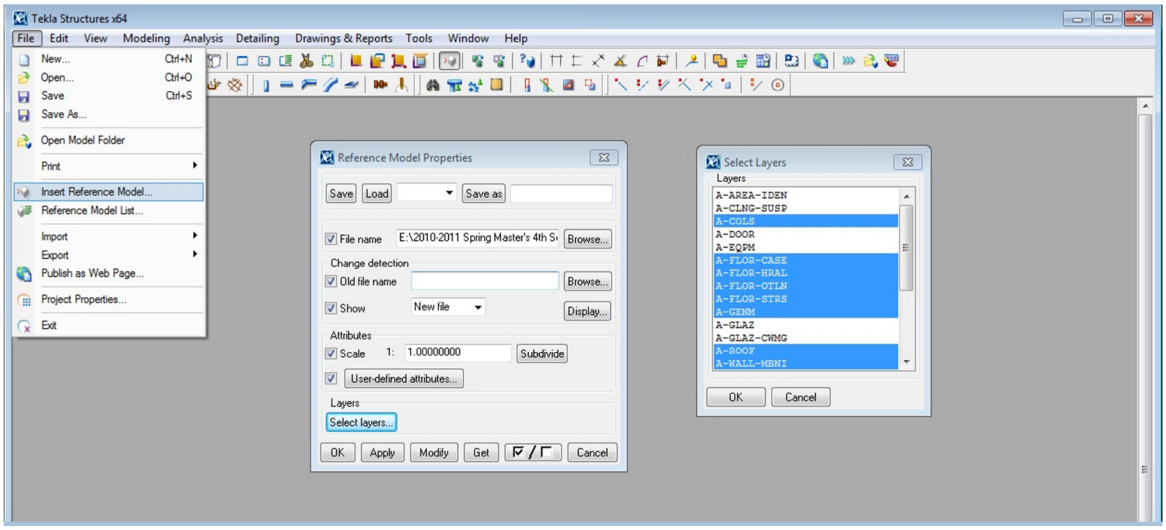

Figure 4 - Reference Model Properties

It would be prudent to convert objects piecemeal one layer at a time to apply the firm's visual modeling preferences to each element. For instance, the structural modeler may want to apply a pre-defined setting for each type of element while only transferring from the IFC model the member size/shape and physical location/orientation. There are still many issues associated with the transfer of information through the IFC class. Because the information is going from a native file format to an open format like IFC and then to Tekla, there are inherent problems such as differences in naming (i.e. A36 Steel vs. Steel_A36).

Management of Data Revisions and Changes

After the import of the Revit model, subsequent changes made to the Revit model will be re-imported and detected using the *Change Detection* section when inserting the reference model. Select the previous version under *Old File* as well as the *Show* option of 'New', 'Old', 'Unchanged', 'Changed', 'Deleted', and 'Inserted'. This step will prove extremely useful when re-importing updated revised architectural reference models. The detected changes between the architectural models will be highlighted and will let the structural engineer identify any changes that need to be made to structural elements, if any. Figure 5 shows how Tekla would display 'Changed' elements between IFC files. The reference model can also be set to show only "unchanged" elements, "deleted" elements, "inserted" elements, or just the old or new IFC models.

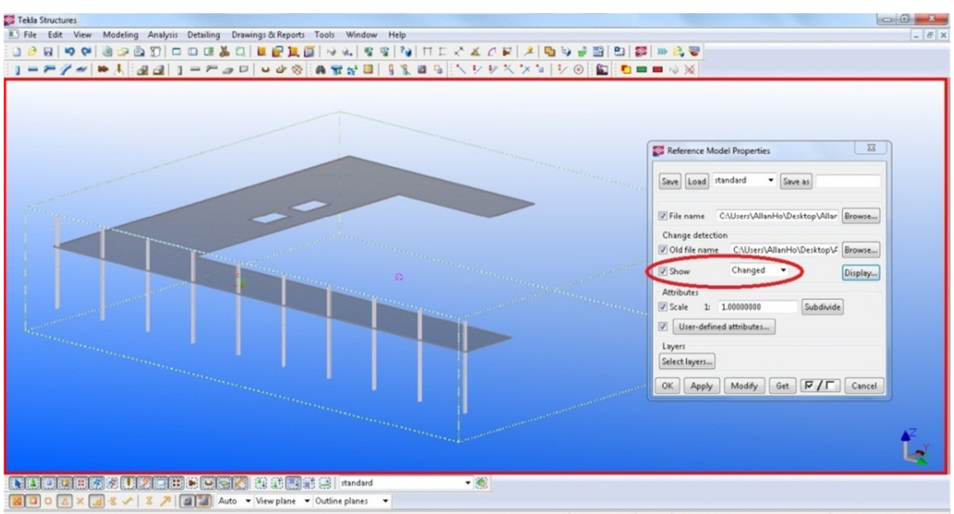

Figure 5 - Reference Model - Change Management Showing Changed Elements

Tekla has released a new and improved method of tracking changes with the "IFCChangeManagement" macro available for download from the Extranet website[1]. The macro graphically displays the change in two IFC models while also providing a text output displaying a 'change management report'. The macro allows filtering to find changes to any Tekla element properties such as material type, position, elevation, length, or profile. Instead of using the Change Detection system described above, the IFCChangeManagement macro may be downloaded from the Tekla Extranet for free. Tekla's reference model 'change detection' system can only isolate elements that have been moved, deleted, or inserted. The 'IFC Change Management' macro is more powerful in that it can essentially sort the selected IFC elements by any combination of given parameters and graphically locates each element in a spreadsheet format.

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[1] *https://extranet.tekla.com/*

Figure 6 shows a list of properties that can be used to check between IFC models. This makes the comparison between IFC models a highly customizable process where certain parameters can be ignored or isolated. The IFCChangeManagement macro requires both IFC models to be loaded as reference models into the Tekla model. The original and new IFC models are selected, respectively, and compared according to the parameters selected. A plain-text file is written each time models are compared and may be saved as a log of changes as each new IFC model is received.

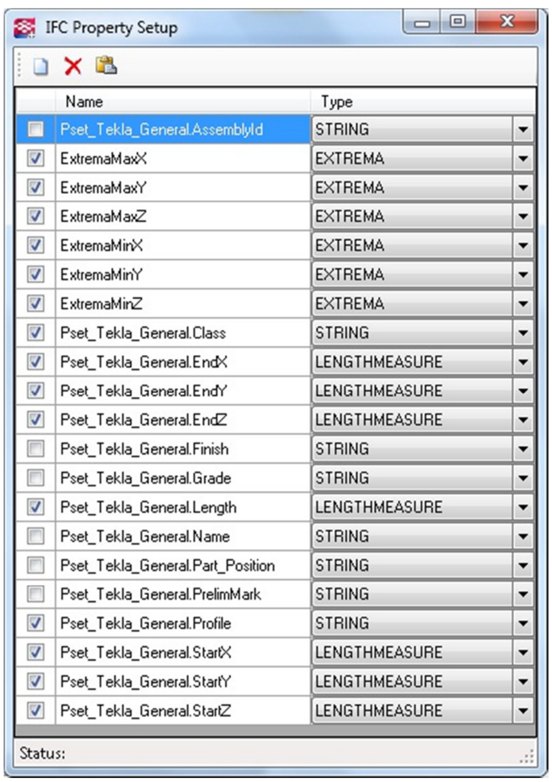


Figure 6 - IFCChangeManagement - Filter Parameters

The main focus of the structural engineer is to provide structural support for gravity and lateral loads while fitting the architectural vision and demands. The architect will export their architectural BIM model into a pre-determined compatible file format such as IFC. The structural engineer will then reference this model and create the structural model. Geometric data can be used for modeling while material properties can be used for weight estimation and analysis. From the structural model, an analytical model can be exported to a structural analysis program for preliminary structural member sizes. This information can be returned to update the structural model with member sizes. The structural model is then exported and sent back to the architect for coordination and comments. Tekla does not import gridlines as they are not true 3D objects. They are usually 2D projections of planes for construction documents, which means grid-lines must be created in Tekla. Column grid-lines define not only column locations, but are reference coordinates to allow for easier discourse between trades. You can import an AutoCAD drawing with the gridlines and trace them in Tekla or create them with given dimensions. In Tekla, go to ***Modeling>>Create Grid...*** to access the Grid dialog box as shown in the following figure. The grid X, Y, and Z coordinates are the relative distances between each gridline. The magnetic option forces objects directly on the plane to move automatically with the gridline.

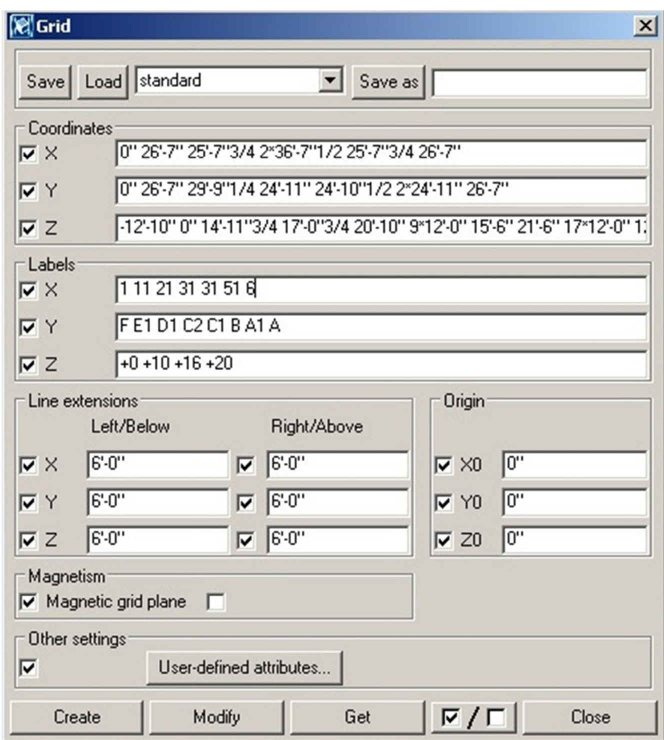


Figure 7 - Grid Dialog Box

As part of the interoperability with other trades, Tekla uses the concept of 'reference models' to transfer information between models from other trades and the Tekla structural model. This concept is akin to 'extended references' or 'xrefs' in AutoCAD. It is simply inserting 3D or

2D information such as the architectural IFC model or a CAD drawing with the added benefit of seeing the changes in model updates. The reference model can be manipulated without editing the original file by filtering layers on or off and also tracking changes between versions of the references.

Using the reference model, IFC objects can be converted, or Tekla elements can be placed on the reference model. To convert IFC elements, highlight objects and use Tekla's IFC Object Convert found at ***Tools>>Convert IFC Objects***.

Currently, Tekla can import nearly all standard linear elements (beams, girders, columns, braces, and hangers) with its standard library. Custom shapes and materials that do not exist in the Tekla libraries will have to be created in Tekla and manually mapped to the element. Converting planar elements like walls and slabs was only recently introduced in Tekla version 17. As with other BIM programs, the technology in Tekla's programming is still incapable of fulfilling the total potential of BIM. There are still many technical limitations in comprehensive modeling of unique structural elements such as curved slab edges and two-way waffle slabs in Tekla.

Figure 8 below illustrates some of the options that may be found under 'Settings' during the IFC Convert process such as checking for missing profiles or materials for which Tekla could not identify a Tekla equivalent. Dimensional tolerances can also be set so that measurements made in models beyond the useful precision of the engineer can be rounded to a reasonable value.

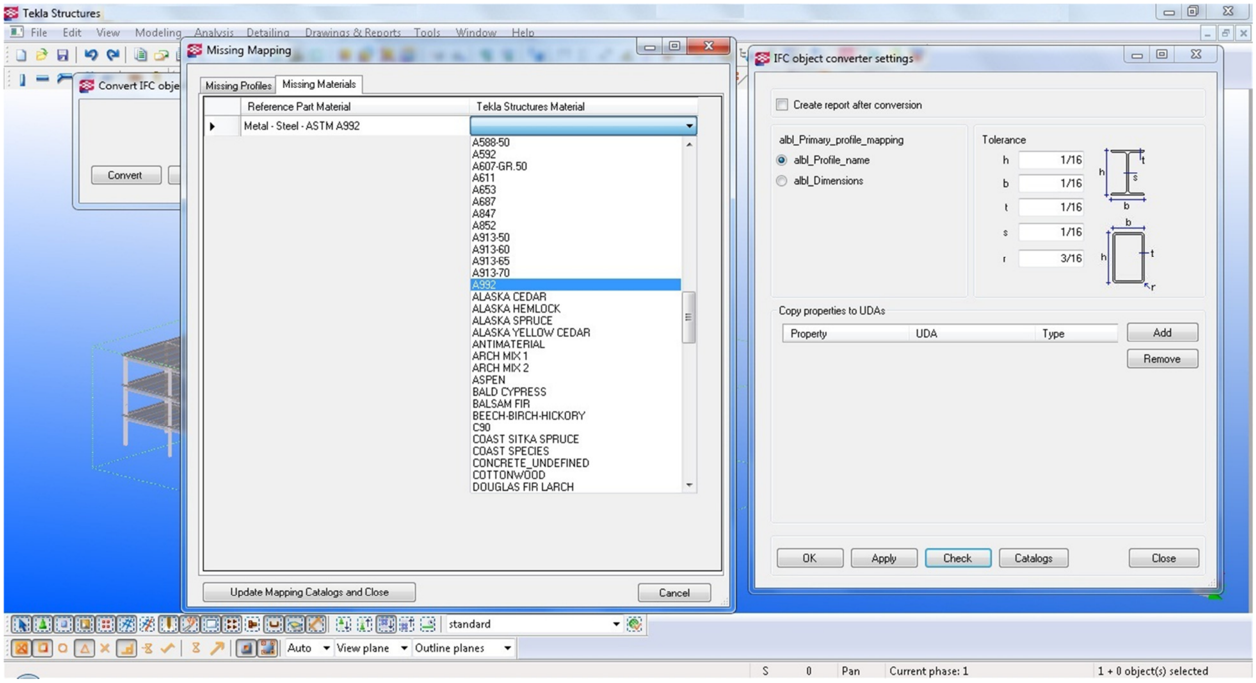


Figure 8 - IFC Converter tool – Dimensional Tolerances and Mapping

After the conversion, the report can be viewed under “Report”. The following figure shows what IFC elements were converted to what Tekla elements. Here, a visual check can be made to see if there were any mistakes or inconsistencies in the conversion process.

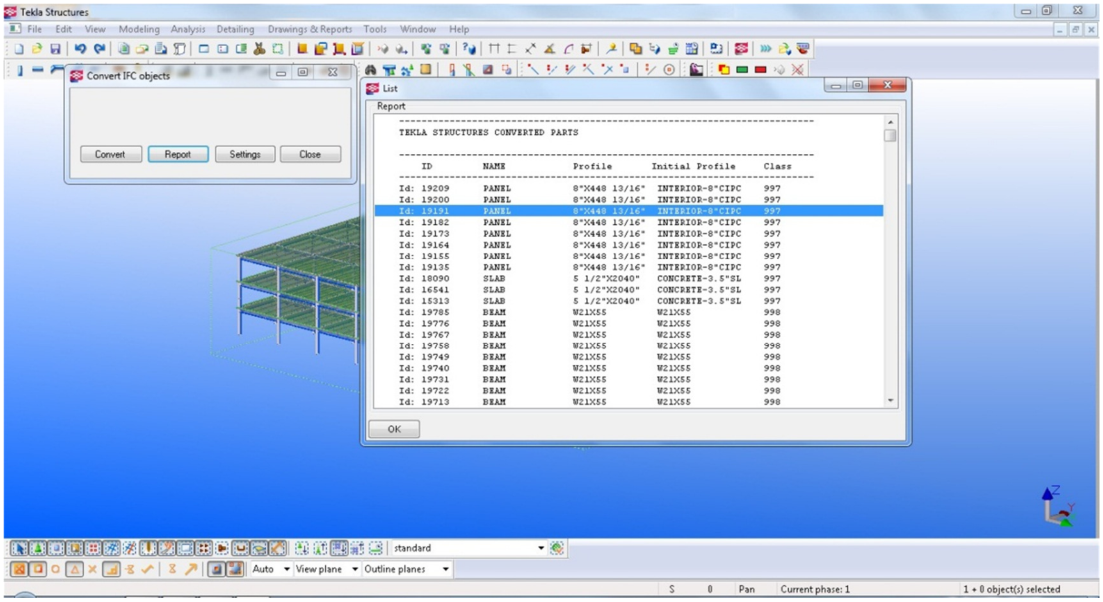
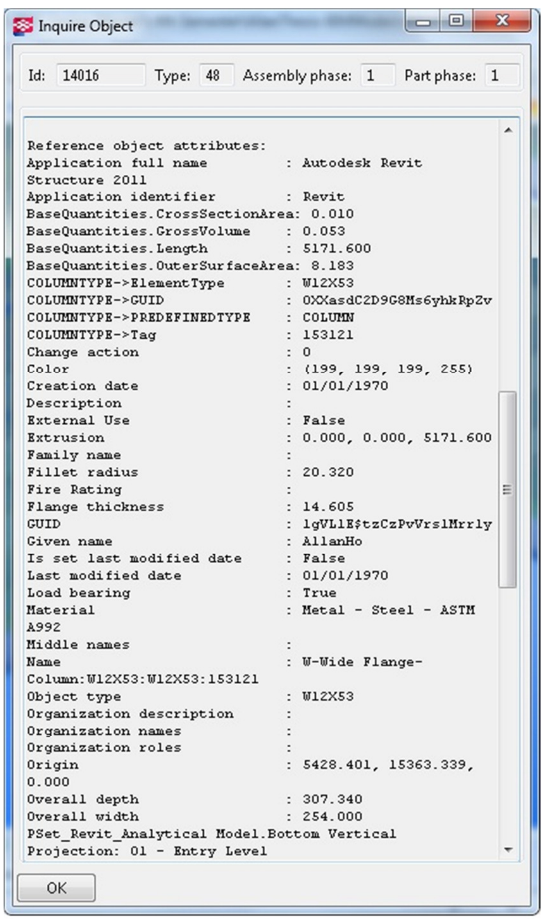


Figure 9 - IFC Convert Report



Later, individual IFC elements may be queried using the ‘Inquire” command on the reference model element. Right-click on a IFC element, making sure that the option of ‘Select Objects In Components’ instead of ‘Select Components’ is active, and select ‘Inquire’. The following figure shows some of the parameters that can be queried.

Figure 10 – IFC Element - Inquire

Once the structural elements have either been converted from the architectural reference model or added as Tekla elements, coordination will start parallel with the initial structural analysis. As architectural changes are made, changes can be detected automatically and the structural elements adjusted as necessary.

Clash Detection Between Multiple Models

Models from other trades can also be inputted when they join the project such as mechanical systems as well as other elements such as sustainable energy systems. The level of detail of each of the models will most likely be decided by the firm and/or decided beforehand by the lead project coordinator.

The structural engineer can add multiple models as reference models and then use the clash check under ***Tools>>Clash Check Manager*** to detect interferences between elements.

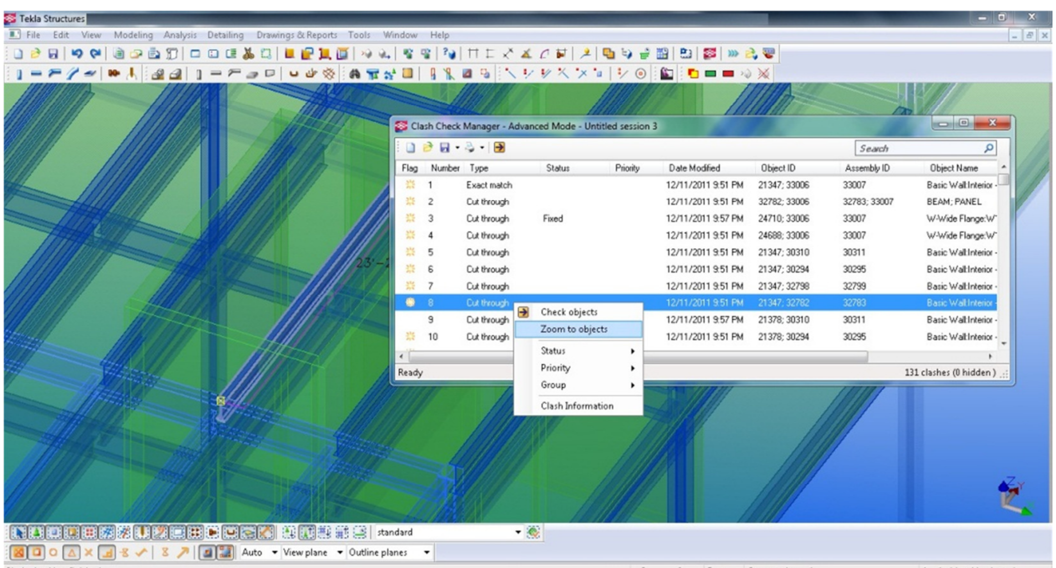


Figure 11 - Clash Check Manager Dialog Box

The clash check manager can zoom to objects identified as clashing as well as give the element object names so you can identify the clashing elements. Based on experience and suggestions from Tekla technical support, it is likely that a clash check should be of specific element types or areas and not a project-wide clash check. This is because of the current nature of modeling is not as precise in every area in order to reduce complexity and file size of the project. There is no guarantee of the level of detail is equal in every geographical location in the project or across all disciplines. Most likely, performing a project-wide clash check would find thousands of false positives that are easily resolved with common sense. A more likely scenario would be an engineer selecting CMU walls in an area and performing a clash check with architectural partitions, finishes, and MEP models in that same area. Again, a piecemeal procedure would be easier to work with and allow a more thorough analysis.

The clash check is not a catch-all solution to coordination, which is the main focus of every construction project. It is merely to identify possible problem areas and is a very basic assessment of geometric overlaps. Some of the clashes identified by the program may be simply modeling simplifications – in Figure 4 above, a clash is detected between the steel column and concrete slab. In reality, a quick engineering judgment will reveal that the slab would simply be poured around the steel column and the clash is a modeling simplification and the error in material volume is nearly negligible. The program may also miss other clashes that may not be revealed by simple geometric overlap checks. For example, clearances for door openings, headroom heights, and construction erection clearances may not be recognized as these involve open spaces that will not clash with any modeled elements. These exceptions serve as another reminder that BIM is just a tool to assist in the project workflow, not a transfer of responsibilities or professional duties.

The next section will discuss the analysis and design portion using Tekla in a structural engineer’s workflow – the structural analysis and design using modeled elements and their associated component information.

PART II. STRUCTURAL ANALYSIS AND DESIGN

Structural Analysis in a BIM Workflow

The traditional approach for a structural engineer is to create an analytical model of the building in a structural analysis program such as SAP2000, RAM Structural System, CSC, or STAAD. The drafting of construction documents follows as a parallel but separate process with the structural analysis; drafting is simply the representation of the structural design – traditionally, there is no connection between the analytical model and the drafted information. Any structural changes require manual updating of models and all associated details, sections, and elevations as well as manual coordination of possible clashes/interferences. This can be a time consuming process but BIM has shown promise in streamlining this operation.

The BIM approach is to create one 3D model that is used for both structural analysis and drafting. Each detail and section would be just views of different portions of the model. This ensures that all changes propagate through all drawings. The analytical model could have a simplified version of many of the more complex areas where the intricacy is important for detailing but less important for structural analysis. For example, many structural analysis programs do not recognize eccentric connections of the beams to the columns during the import process. It would be better practice to simplify the structural analysis model to have beams connect directly to columns and account for the eccentric connection during the lateral analysis and connection design. Another issue with importing the entire 3D model into structural A&D software is the lack of necessity to model every part of the project. For most applications, it is enough to simplify the problem to a very simple structural model that does not need to be 100% accurate in terms of minute details but represents the physical condition of the area under scrutiny. This is where a large portion of engineering judgment takes place to ensure that a conservative approach to a given problem is utilized and that the design is reduced in terms of complexity but not in terms of safety or accuracy. That being said, it would be wise to perform the export from Tekla to structural analysis software as few times as possible. Often a handful of analyses will be required for conceptual design to give the architect an idea of the size of elements required and feasibility of the project.

The most important feature of incorporating the analysis and design of the project into the BIM cycle is the fact that now all A&D models will remain up to date with the need to modify both the drafting representation of the structure and the analysis portion. The implications of such a system are that with the central database of information, multiple models in different programs may be generated, each having direct connection to the current model information. This means reducing the waste of time spent updating each model for every different portion of the project. If the foundations, gravity system, lateral system, beam connections, and cladding are designed in five separate programs, each can have its own Tekla Analysis model associated with it. Each Tekla Analysis model will have only the pertinent elements assigned to it, but all elements are part of the Tekla database. This multiple analysis models from one database allow many different portions of the project to be analyzed simultaneously but maintain consistency and easily maintain model integrity.

In Tekla Structures, it is possible to define load magnitudes, load cases, load combinations, and different load types (distributed, line, point, area, etc…). There are two possible routes to go with the structural analysis. The first choice is the full BIM choice where the restraints and loads (cases and combinations) are defined within Tekla and only exported to a structural analysis program for analysis. The second choice is to export the geometry and member information from Tekla and create all loads and combinations in the structural analysis program. There are advantages and disadvantages to both paths. The only reason to choose Option 2 would be the lack of software compatibility with the engineer's structural analysis program. If Tekla has not yet developed a fully functioning API link to the A&D program, the engineer has no choice but to export the geometry and member data only. If the engineer's firm has a program such as STAAD, SAP2000, or Robot that has the proper API to perform a back-and-forth with Tekla, then Option 1 may be chosen.

The model export process is as important as the analysis portion. To export the model to analysis and design software, first a Tekla Analysis model must be created, which can then be exported to design software such as SAP2000. In Tekla, the summarized process of creating an analysis model is as follows (Tekla Structures Manual, Tekla, 2011):

1.) Create the main load-bearing parts in Tekla.
2.) Create the load model.
3.) Create the analysis model & define properties.
4.) Set support conditions for parts and connections.
5.) Create load combinations.
6.) Check the analysis model in Tekla structures for integrity and modify/simplify as necessary for analysis export.
7.) Export to Structural Analysis & Design software.

At this point, the superstructure of the Tekla model should have been created. The first step in creating the creating the analysis model is **Analysis>>Analysis & Design Models.**

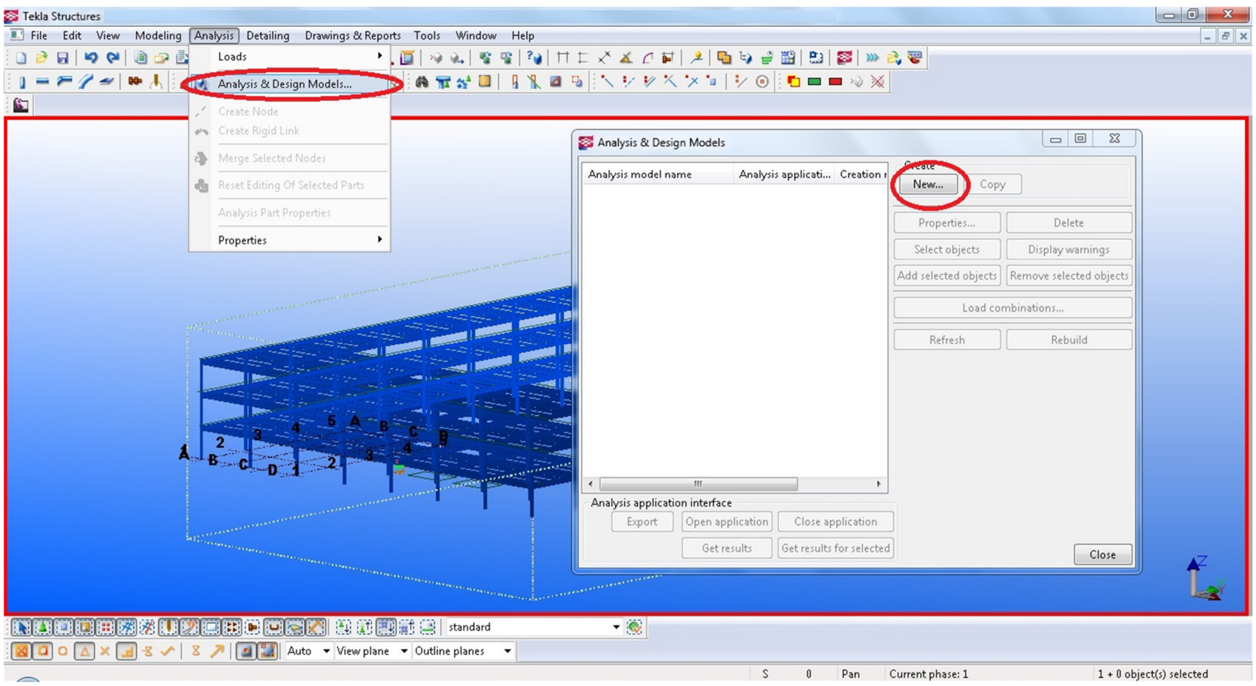


Figure 12 - Analysis & Design Dialog Box

Here, multiple structural models can be created depending on whether the user wants a full model of the entire project, or just selected parts or even select loads. This separation of analysis models using the main model as the basis is another powerful concept in BIM as it allows a finer degree of control for the structural engineer in terms of analysis techniques and approaches. The engineer can diversify his/her analysis using specialized programs as necessary on the appropriate area of the project. For example, the lateral system can be analyzed in ETABS and the gravity system in SAP2000 depending on preference. Select **Create>>New…** to begin the analysis model creation process. This opens the Analysis & Design Models dialog box shown in the figure below.

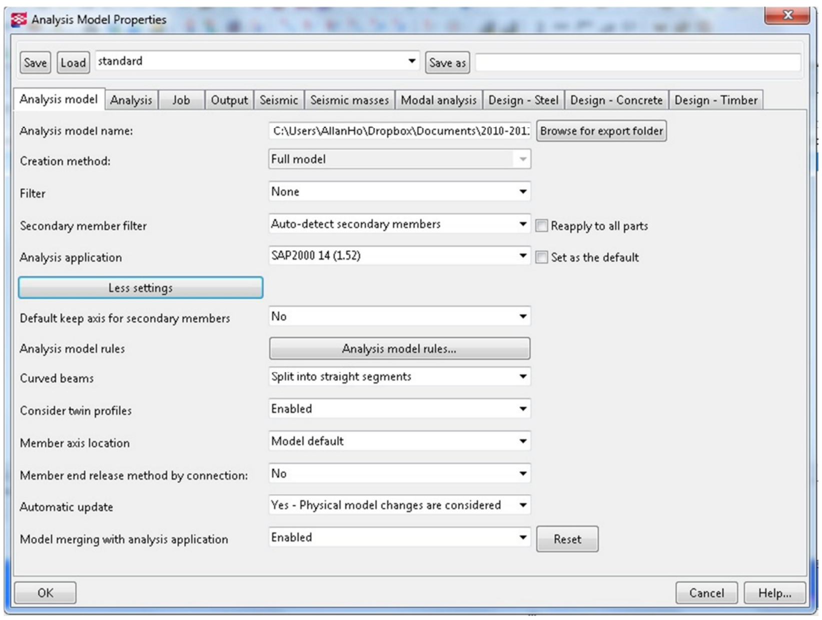


Figure 13 - Analysis Model Properties

To change the elements selected, choose the "Creation Method" shown in Figure 13, where the user can select one of the following options: full model, by work area, by selected parts, by selected pars and loads, or floor model by selected parts and loads. Create analysis models by selected parts and loads to create partial models as needed. Enable model merging to allow changes in SAP2000 to export back to Tekla.

The information that is returned to Tekla after analysis can be viewed and selected on the Outputs Tab shown in the following figure.

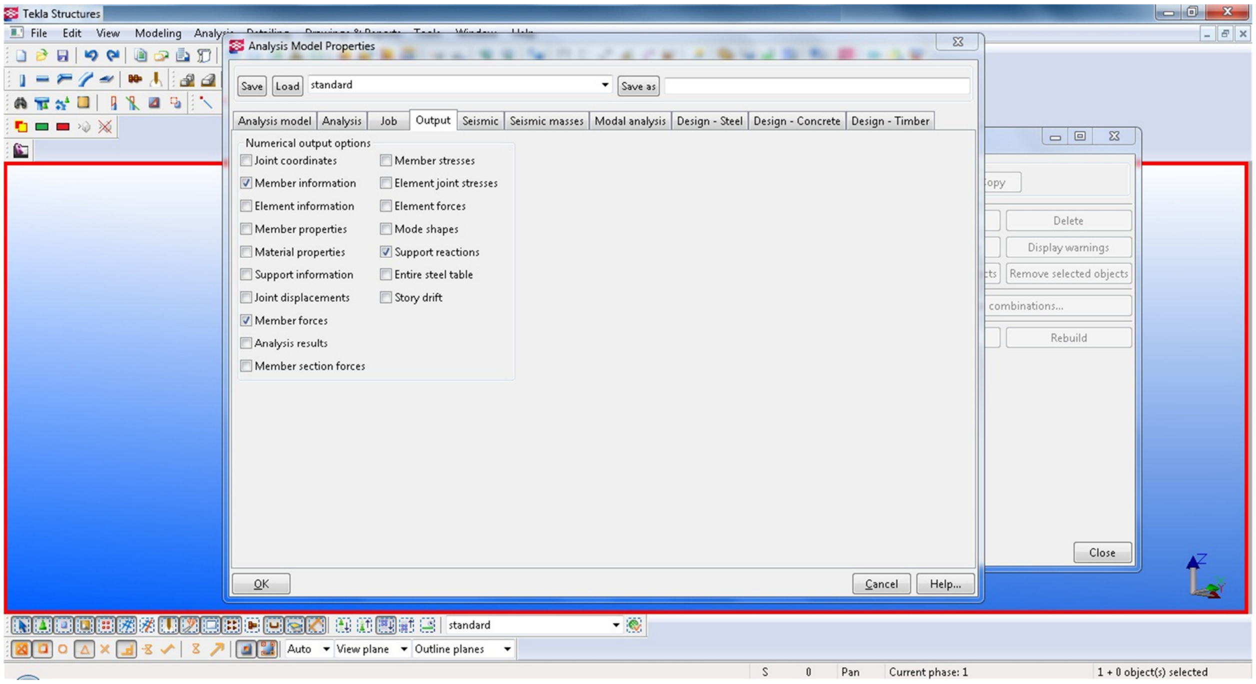


Figure 14 - Analysis Model – Output

The importance of these parameters is that it allows the structural engineer to decide what values will be useful for the Tekla model. The element forces may be important to display as an end reaction on Plan drawings for the steel detailer to design connections. The member information may be important for updating the element size/shape. The support reactions may be important to label on a plan drawing for the geotechnical engineer to determine the foundation type or check existing soil conditions for the loads.

Options relating to the analysis model can be modified to suit the needs of the structural engineer. Different analysis software can be chosen as well as options related to steel, concrete, and timber design codes & defaults. The figure below shows the selected AISC Allowable Stress Design 1989 code is selected as well as the given information regarding that specific steel design code.

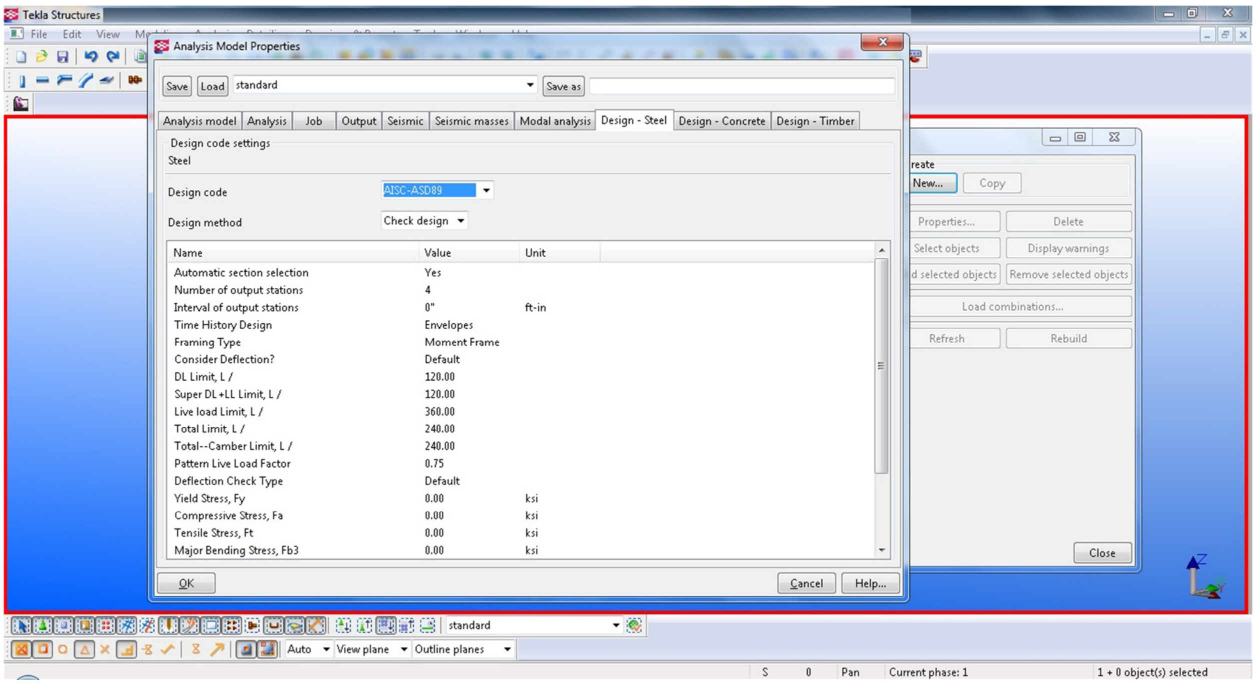


Figure 15 - Analysis Model Options - Design – Steel

Also important to note is the fact that these settings may be saved at the top of the dialog box as are most property dialog boxes in Tekla. This allows the engineer to specify these settings once and save them with a descriptive name for later use.

Now it is important to create the load groups and combinations. The self-weight of all modeled elements can be toggled in settings. Create the individual load cases from the design code you would like to use. 'Load groups' in Tekla are synonymous with 'load cases' in ASCE 7-05 and AISC.

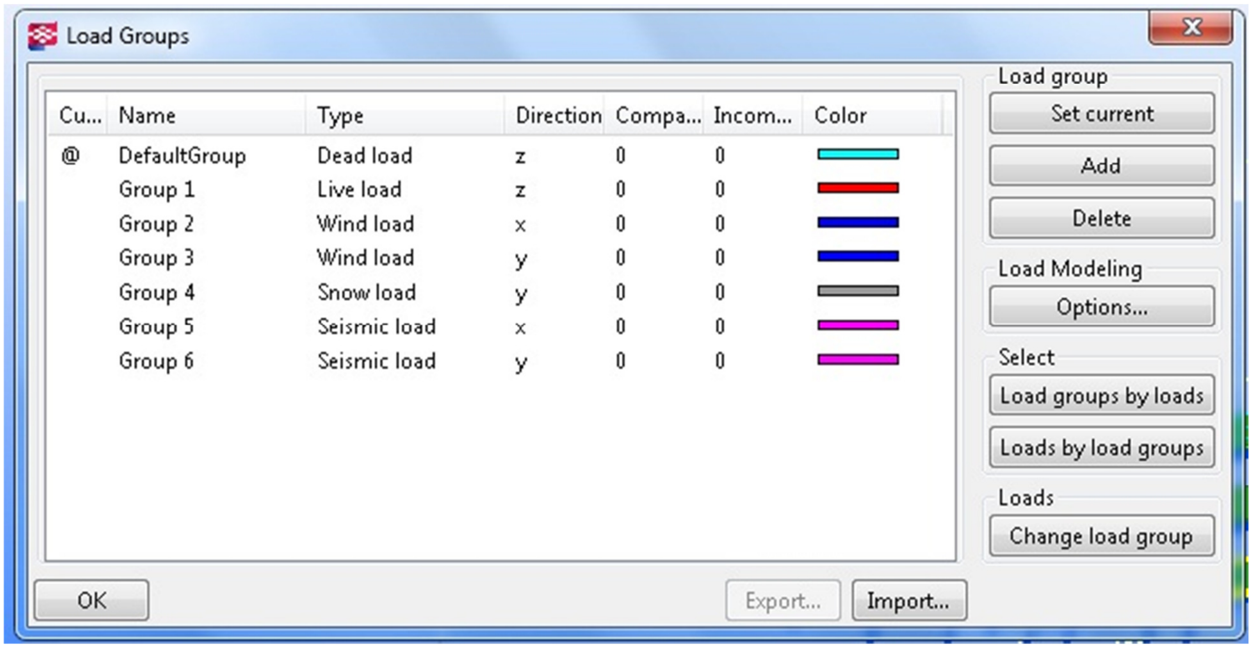


Figure 16 - Load Groups Dialog Box

The main loads for a building are the anticipated Live Load that will be listed on the Certificate of Occupancy of the address, the wind loads for the main lateral wind resisting system (MWRS), dead load (wall partitions, hung mechanical piping, HVAC mechanical equipment, floor finishes, and self-weight of structural members), seismic load, rain/snow/ice load, and any concentrated loads that might occur. Next, define the load combinations either by selection the appropriate code or defining each load combination. The figure below shows the AISC LRFD code load combination factors.

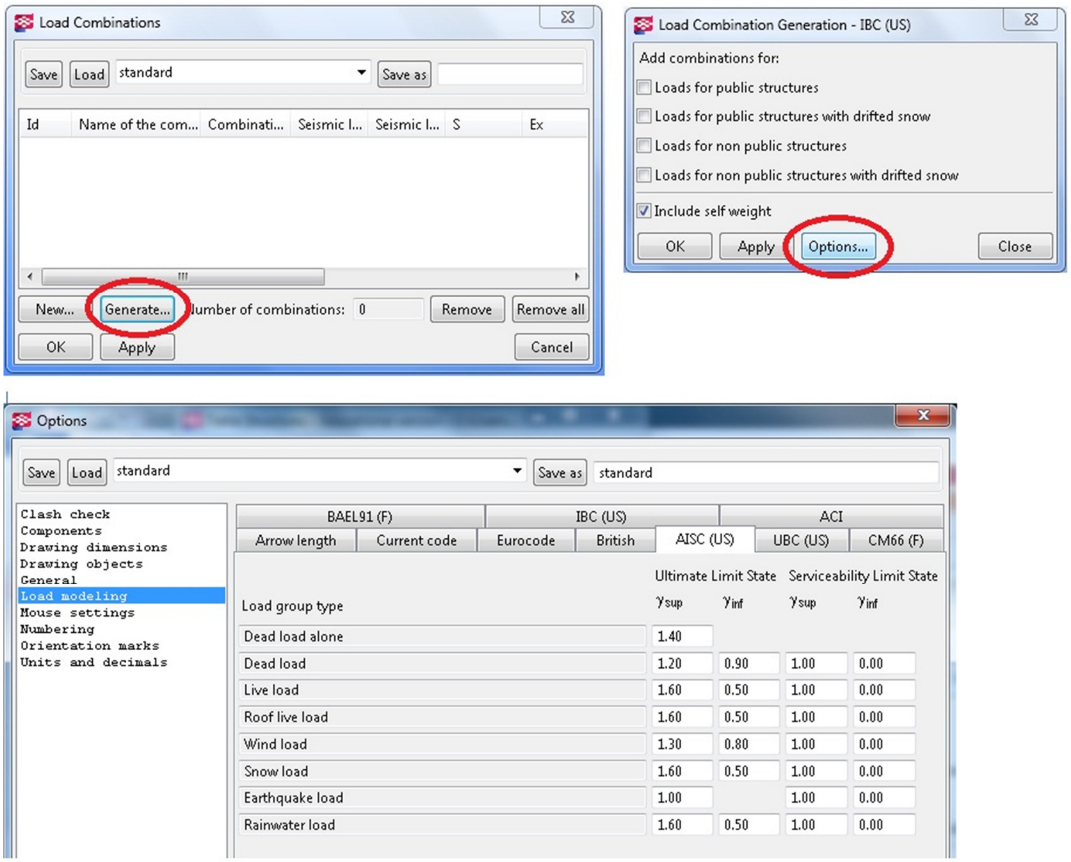


Figure 17 - Load Combination Generation

After defining load combinations, the loads must be applied to the Tekla elements. The analysis model is displayed as simplified centerlines while the elements are shown as wireframes. Loads can be applied as standalone loads in 3D space (absolute coordinates) or applied on the elements (local coordinates). The loads may be attached to elements/parts under the analysis properties of each load by right-clicking the analysis centerline and selecting **Properties** shown in the figure below.

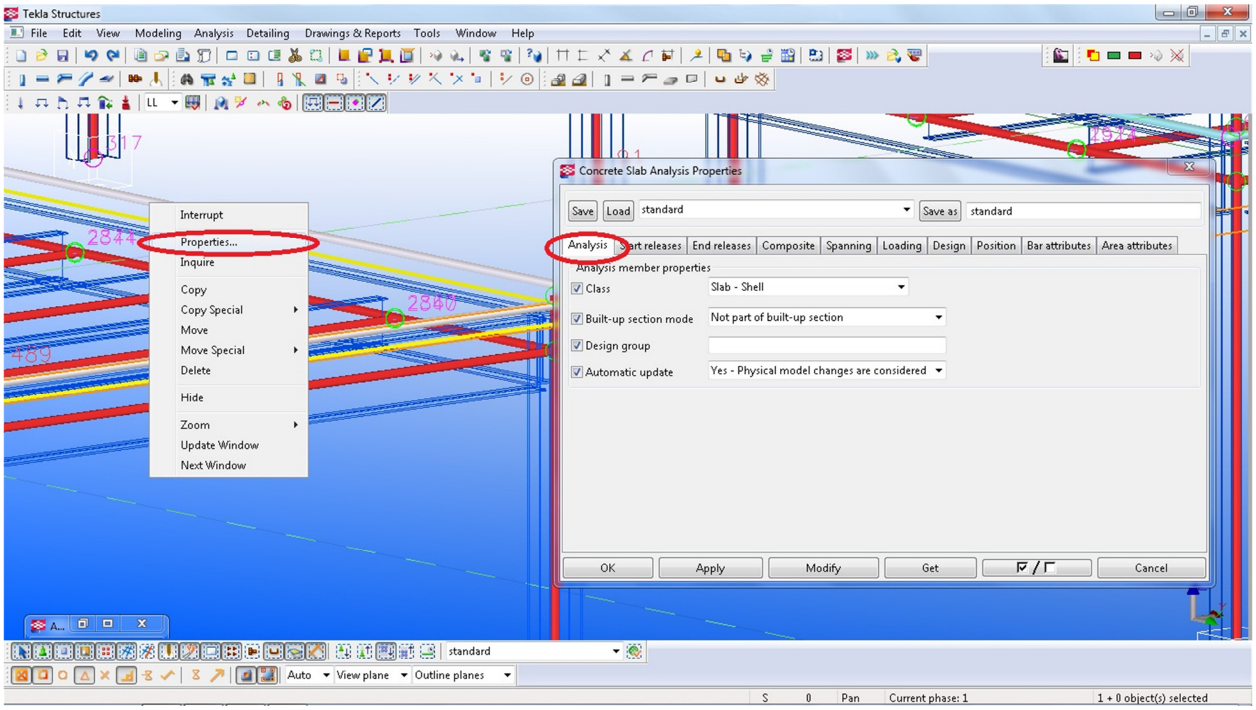
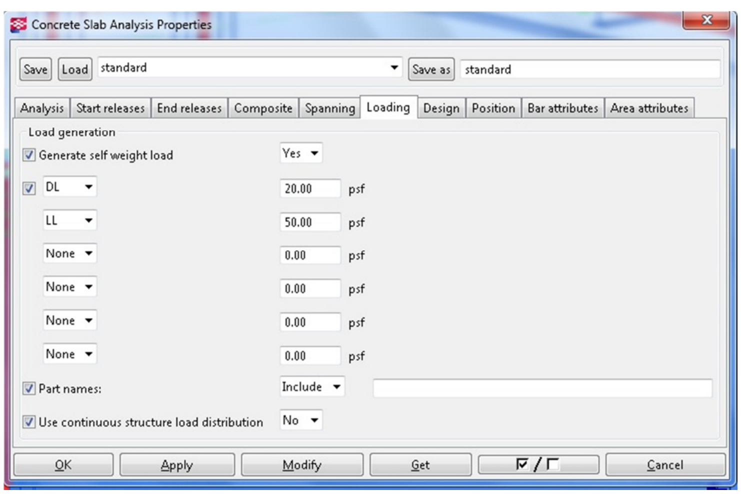


Figure 18 – Slab Analysis Properties Dialog Box



In the adjacent figure, loads may be applied to the element for each different load group. While applying loads, the load path should be considered.

Figure 19 - Slab Analysis Properties - Loading Tab

Load paths may be transferred through the connectivity of the element. For example, the figure below shows the **Position** tab of the Analysis Properties.

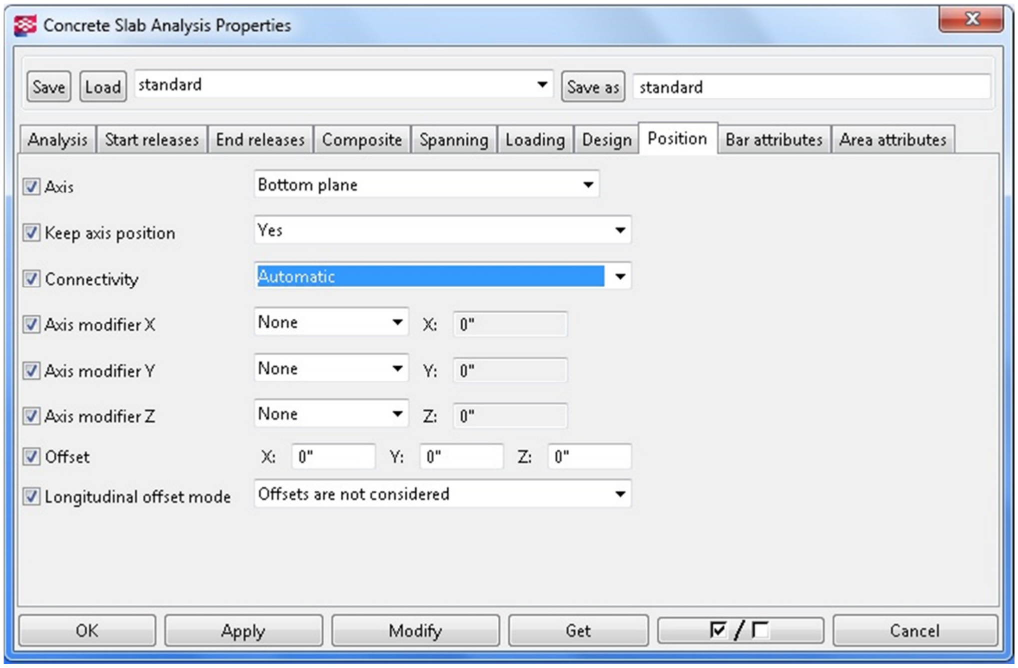


Figure 20 – Slab Analysis Properties - Position Tab

The connectivity transfers load from the slab to the beam by setting the Axis to Bottom plane and the Connectivity to Automatic. This allows the movement and alteration of the element and a consequential adjustment to the load. The default setting is for loads to be positioned in absolute space. Figure 21 below is the whole Tekla analysis model.

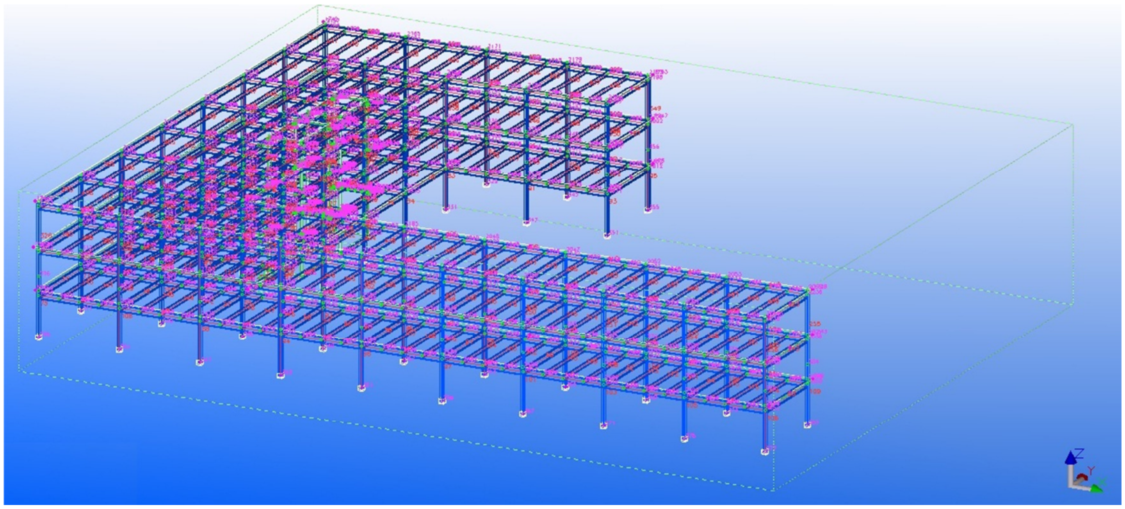
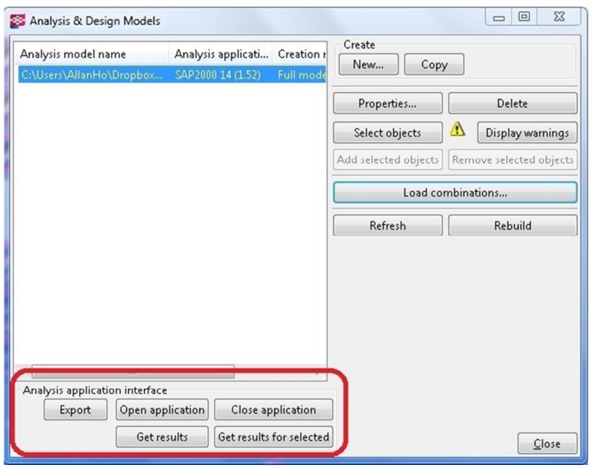


Figure 21 – Overview Analysis Model

Tekla automatically creates support nodes at the end of the columns but the nodes should be checked for accurate and realistic support conditions depending on the foundation system and soil conditions. In the figure, the support nodes are all set to "fixed" to reflect the assumption that there will be piles driven at each column base. More modeling-analysis issues may arise such as beam setbacks not being considered as connections. These types of problems may be corrected through the use of rigid links or setting tolerances in the advanced analysis options.

Export to SAP2000

Once the analysis model is created, the analysis model may be exported to the chosen analysis software in at least five different ways. Tekla uses "Analysis application interface" to interact with the A&D software as shown in the Analysis & Design Models dialog box below.



Export	Exports the model to the analysis application.
Open application	Starts the analysis application and opens the selected analysis model in it.
Close application	Use to exit the analysis application.
Get results	Saves the maximum axial force, shear force, and bending moment at the part ends as user-defined attributes in the part properties. To view these results, open a part's user-defined attributes dialog box. See **Get results**.
Get results for selected	Same as **Get results** but only saves results for the selected parts.

Figure 22 - Analysis Application Interface - Export to A&D Software

The right side of the figure above shows what each export option executes, depending on the preference of the engineer. The option may also depend on the stage of the analysis workflow at which the export is being performed. A practical example of using various export options would be this; a full export may occur after 75% design is completed, the model is configured/manipulated in SAP2000 for analysis purposes, subsequent exports would utilize "Get Results" to pull result data in Tekla.

The actual structural analysis and design in SAP2000 is left as an exercise to the reader. The next step in the BIM workflow would be to finalize the design to prepare for an export of member sizes and reinforcement details back into Tekla.

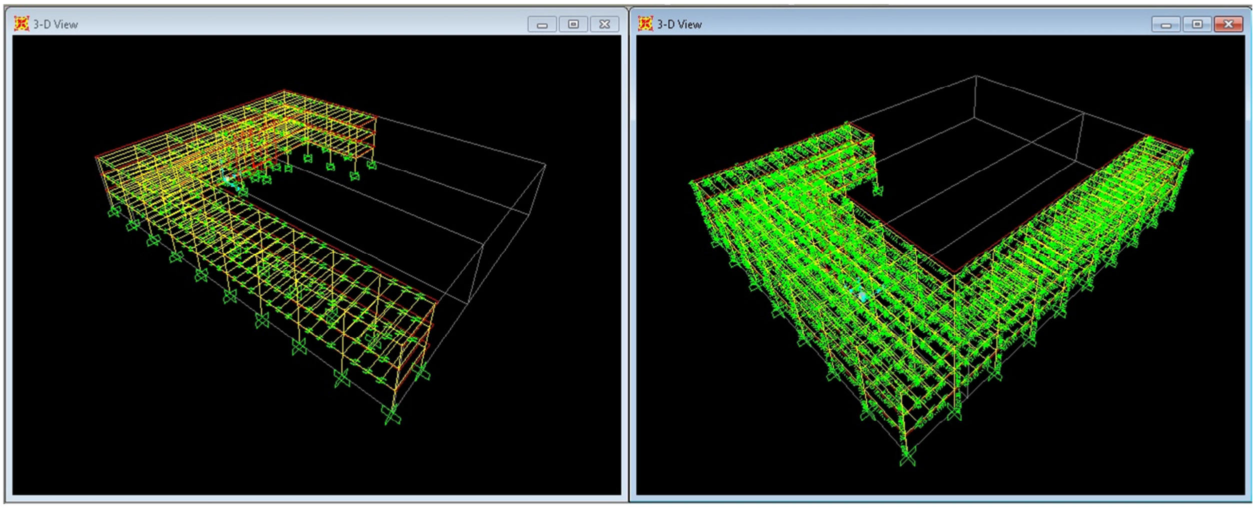


Figure 23 - Tekla Analysis Model Exported to SAP2000

For simplicity sake and to speed up the analysis and import/export process, a partial model of just one column bay will be created and used as the example analysis model. The next figure shows the activity list of the export from Tekla to SAP2000 where data is displayed including part counts, errors, and warnings.

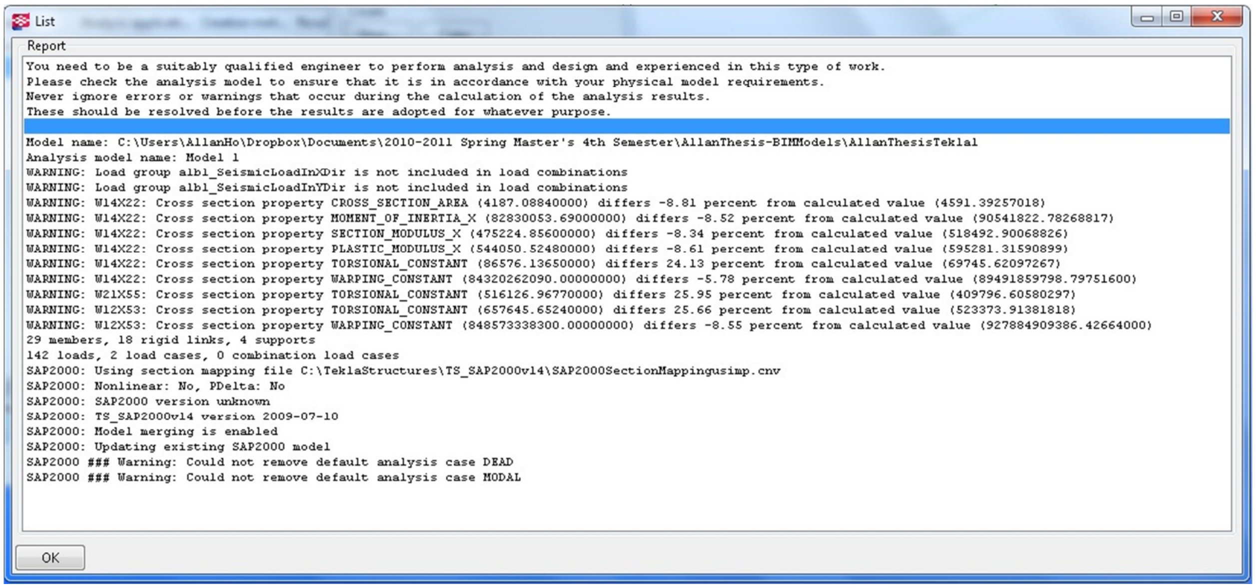


Figure 24 – Analysis Export List

As seen in the figure above, section properties were apparently different in Tekla and SAP2000.The import/export and model merge process is far from perfected. Currently there are known issues with load cases from Tekla and SAP2000 conflicting due to different names for the same type of load (one for Tekla loads and one for SAP loads) where loads created or deleted in SAP will not be recognized when exported back to Tekla. It is still the responsibility of the engineer to ensure the analysis performed accurately reflects design intentions.

When the structural analysis is completed and the element sizes are re-imported into Tekla along with the reaction forces, connection design can be performed. Many of the standard connections can be automatically designed using Tekla's 'Design by Excel' technique where the information stored in Tekla's model can be exported to Excel to be processed through custom calculation spreadsheets and returned to Tekla.

PART III. DETAILS AND DRAFTING

The strength of BIM workflows is the multiple uses of one set of information. Data is not recreated specifically for each purpose – it is remolded or converted to the appropriate form so that it may be used for different functions. The more complex the project, the more efficient this "recycling" of database information becomes. Examples of useful component design using parameter data would be designing slab edge conditions, railings, beam connections, columns splices, column baseplates, spread footing foundations, and

Connection Design by Excel

Like many structural BIM programs, Tekla has a system of allowing access to the information stored in the model called Tekla Open API. Tekla Open API uses Microsoft .NET technology in conjunction with database applications such as MathCAD and Excel to allow the user to produce plug-ins and user-generated applications to suit the firm's needs. This is a major advantage in using BIM on a project as it is leveraging the full power of the available information without requiring wasteful manual transferring of information. Specifically, using Excel for connection design in Tekla is melding structural analysis with structural detailing. In New York, standard connection design traditionally falls under the responsibility of the steel fabricator/erector with the structural engineer's approval through the shop drawing review process. BIM allows the structural engineer to not only design the structural system, but to prepare all the geometry and parametric data required by the detailer during the design process. This is an example of the shift in labor and project scheduling from pre-construction to design. Currently, the steel fabricator must use paper drawings or CAD files with geometric data and written annotation regarding material type, member sizes, and other specifications. With BIM, this parametric database is established once and available for all project members to use – so that all data is cumulative and not simply derivative.

The following is a summarized implementation of a sample connection detail.

1.) The user must complete a few tasks to set up the model for the Excel communication. First, model the structure(s) in Tekla – joists, girders, joists, braces, slab, walls, and columns.

2.) Create the analytical model and export to a compatible structural analysis program.

3.) Import the element information (the required parameters depend on the component using the Excel Design option) from the analysis program back into Tekla.

4.) Model the connections using pre-defined or custom connection components.

5.) Enable 'Design by Excel Option' by opening the component properties dialog box, going to the Design Tab, and selecting 'Excel' under 'External Design'.

Tekla's pre-defined components are all Design by Excel enabled and can be used with the addition of the calculation spreadsheet to the component design spreadsheet. Custom components require a bit more work as the component design spreadsheet must be created using the component template spreadsheet. The figure below shows Tekla default AutoConnections modeled, which can be designed using the "Design By Excel" option.

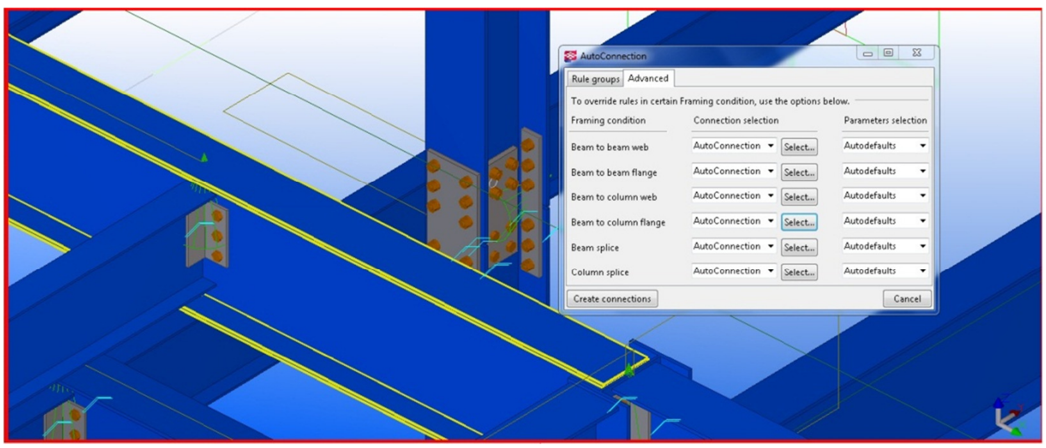
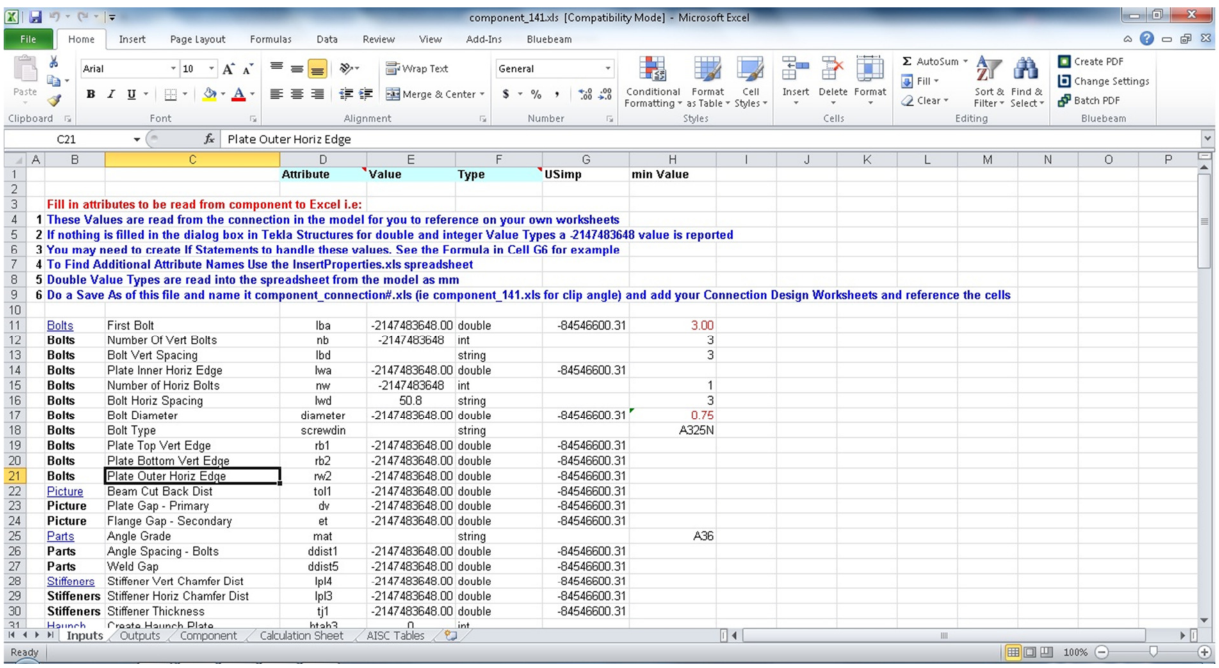


Figure 25 - Tekla Connections

First, the excel design spreadsheet must be finished. Next, the necessary inputs for the spreadsheet can be mapped from Tekla. That is to say that the variables or 'attributes' listed on the Inputs sheet of the excel spreadsheet are the variables that excel will pull from Tekla for calculation purposes. The figure below shows the inputs for Tekla connection component 141, which is a double clip angle beam end connection.



			Attribute	Value	Type	USimp	min Value
1			Attribute	Value	Type	USimp	min Value
3	Fill in attributes to be read from component to Excel i.e:						
4	1	These Values are read from the connection in the model for you to reference on your own worksheets					
5	2	If nothing is filled in the dialog box in Tekla Structures for double and integer Value Types a -2147483648 value is reported					
6	3	You may need to create If Statements to handle these values. See the Formula in Cell G6 for example					
7	4	To Find Additional Attribute Names Use the InsertProperties.xls spreadsheet					
8	5	Double Value Types are read into the spreadsheet from the model as mm					
9	6	Do a Save As of this file and name it component_connection#.xls (ie component_141.xls for clip angle) and add your Connection Design Worksheets and reference the cells					
11	Bolts	First Bolt	lba	-2147483648.00	double	-84546600.31	3.00
12	Bolts	Number Of Vert Bolts	nb	-2147483648	int		3
13	Bolts	Bolt Vert Spacing	lbd		string		3
14	Bolts	Plate Inner Horiz Edge	lwa	-2147483648.00	double	-84546600.31	
15	Bolts	Number of Horiz Bolts	nw	-2147483648	int		1
16	Bolts	Bolt Horiz Spacing	lwd	50.8	string		3
17	Bolts	Bolt Diameter	diameter	-2147483648.00	double	-84546600.31	0.75
18	Bolts	Bolt Type	screwdin		string		A325N
19	Bolts	Plate Top Vert Edge	rb1	-2147483648.00	double	-84546600.31	
20	Bolts	Plate Bottom Vert Edge	rb2	-2147483648.00	double	-84546600.31	
21	Bolts	Plate Outer Horiz Edge	rw2	-2147483648.00	double	-84546600.31	
22	Picture	Beam Cut Back Dist	tol1	-2147483648.00	double	-84546600.31	
23	Picture	Plate Gap - Primary	dv	-2147483648.00	double	-84546600.31	
24	Picture	Flange Gap - Secondary	et	-2147483648.00	double	-84546600.31	
25	Parts	Angle Grade	mat		string		A36
26	Parts	Angle Spacing - Bolts	ddist1	-2147483648.00	double	-84546600.31	
27	Parts	Weld Gap	ddist5	-2147483648.00	double	-84546600.31	
28	Stiffeners	Stiffener Vert Chamfer Dist	lpl4	-2147483648.00	double	-84546600.31	
29	Stiffeners	Stiffener Horiz Chamfer Dist	lpl3	-2147483648.00	double	-84546600.31	
30	Stiffeners	Stiffener Thickness	tj1	-2147483648.00	double	-84546600.31	

Figure 26 - Component 141 - Inputs Sheet

For custom components, a separate procedure is used to ascertain the name of the attributes. To find attribute names, find the "InsertProperties.xls" excel file somewhere in the Tekla file folders. The excel spreadsheet was a macro function in

Tekla versions 16 and older while Tekla 17 maintains the spreadsheet as a standalone file. The excel file is used to map attribute names from custom components by using unique values saved to a property file. The user inputs unique values for the attributes and the excel file will show the unique value and the attribute name associated with that value so that the user can correctly identify input names.

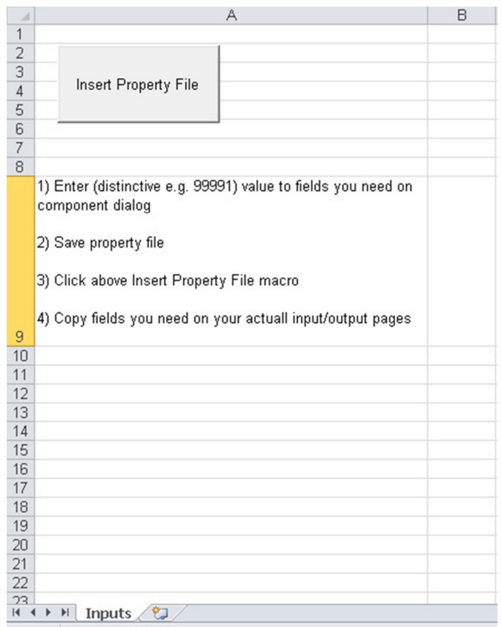


Figure 27 - InsertProperties.xls - For Attribute Mapping

The next sheet in the component excel spreadsheet is the Outputs sheet, where values you want the excel design to update in the Tekla model.

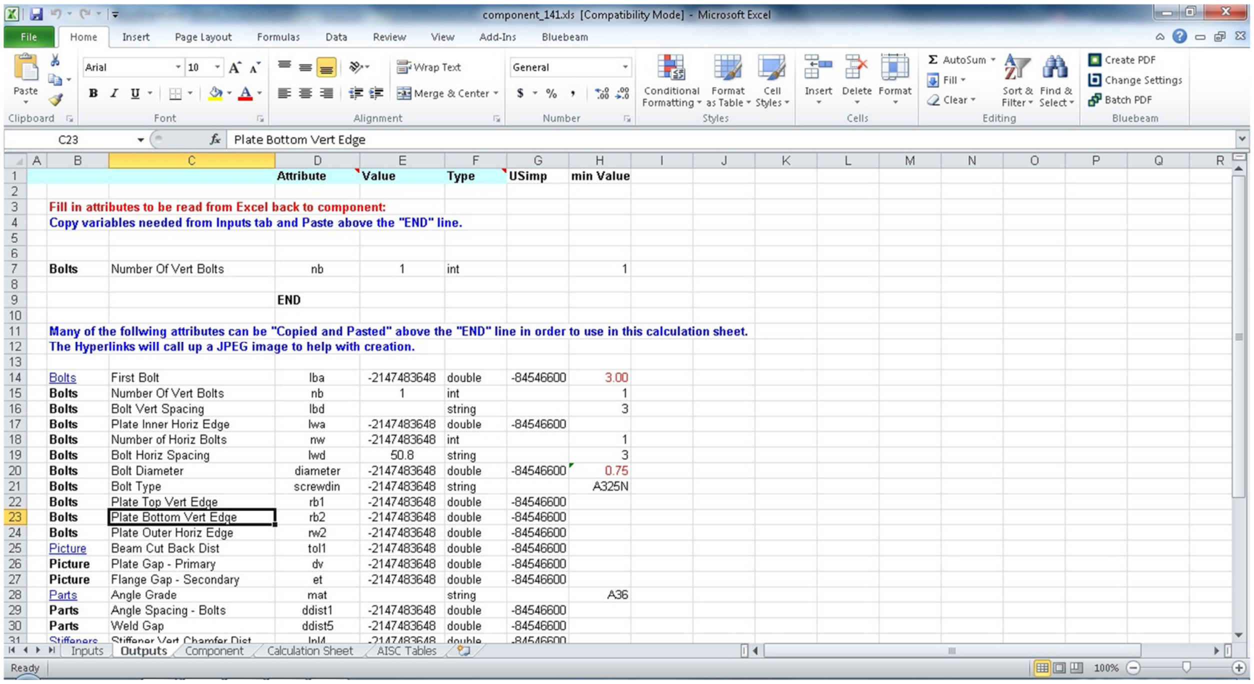


Figure 28 - Component 141 - Outputs Sheet

For connections, this is usually just the number of bolts but as many outputs as desired can be added. As shown in the directions, the variables simply need to be above the "END" line.

The calculation sheet is last sheet in the excel spreadsheet and is where the structural engineer performs calculations to determine the design and thus outputs to return to Tekla. This sheet is where some engineering choices may be made such as minimum bolts given the beam size or minimum weld sizes/lengths.

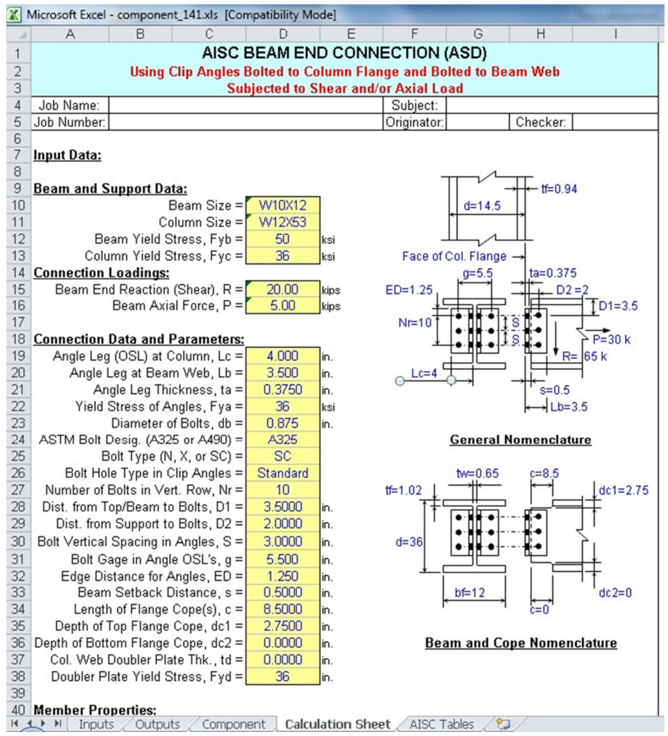


Figure 29 - Component 141 - Excel Calculation Sheet

After completing the excel design spreadsheet, the component must be selected in the Tekla program and the design by excel option will automatically invoke the spreadsheet (the name of the spreadsheet is important as Tekla was search for the spreadsheet based on the format of component_#.xls where # is the component number). 'Debugging mode' forces Tekla to open the excel spreadsheet when the Design By Excel Option is selected. This lets the user see the steps where the Tekla parameters inputs are shown, and the outputs after the design is completed. It is means of double checking the spreadsheet is working as intended.

OVERALL STRUCTURAL ENGINEER'S BIM PROCEDURE

1.) During the pre-design phase of the project, the BIM objectives and standards must be decided and agreed upon by the architect and project consultants. A system of transferring the project files must be established as BIM models can as much as a few hundred megabytes of data; far beyond what most company email systems can attach or handle. Project files may be shared by ftp sites hosted by the architect or project management systems such as Newforma's Project Center that can handle large filesizes and allow a centralized location for project files.

2.) Optional – project owners, managers, and construction management may be involved early during the design process. Use the 'Publish to Tekla BIMsight' add-on to allow free viewer access to the Tekla model. Read-only access allows early cost-estimation and construction scheduling to begin without prematurely releasing the full model data.

3.) Obtain architectural IFC file. In Revit, go to File>>Export>>IFC Options to modify the IFC class associated with each Revit family. Run '**Export to Tekla Structures'** add-on in the Revit program to obtain an IFCzip file.

4.) Insert the IFC or IFCzip files as a reference model into Tekla to a predetermined (x,y,z) coordinate. **File>>Insert Reference Model…**

5.) Convert reference components to Tekla model elements. **Tools>>Convert IFC Objects**. Isolate single layers in Revit IFCzip file such as S-Col, S-Beam, or A-Flor-Otln to convert the reference objects one type at a time – this allows a piecemeal conversion process that facilitates the proper maintenance of Tekla modeling standards. The standards can include such things as column handle orientation, which may allow Open API Macros that design footings to properly execute. Different attribute settings may be saved at the top of the element properties dialog with different names and loaded as required – uncheck the properties that should be pulled from the Revit reference model (profile name, material, and position) to load Tekla standards while still applying the metadata from the Revit model.

6.) Perform a Check Catalog to ensure that IFC classes are being properly mapped to Tekla elements and materials. Check for missing profiles and missing materials. Assign Tekla profiles and materials to missing profiles and materials as appropriate.

7.) Model unconvertible and additional elements. Examples include slab openings, gridlines, and unique one-off elements such as trusses. Import architectural AutoCAD files and arrange them in 3D to model gridlines and assist with dimensioning.

8.) Gather information for loads from model material information. Right-click on elements to inquire volume, area, and weight. Tekla automatically calculates dead load from self-weight.

9.) Add structurally pertinent information from the mechanical, electrical, and plumbing engineers such as loads from heavy mechanical equipment (electrical pumps, heat exchangers, cooling towers, and water tanks), electrical riser or duct shafts, dunnage steel, and support for piping & conduits.

10.) Create analysis model – **Analysis>>Analysis&Design Models>>Create>>New…** In the analysis model, assign boundary support conditions, member end fixities, and define all load groups & combinations. Include dead loads, live loads, wind loads, seismic loads, soil loads, flood loads, snow loads, rain loads, and atmospheric ice loads.

11.) Select 'Analysis Application' as **SAP2000 14 (1.52)**. Select desired design codes for steel, concrete, timber, and seismic design. Select desired numerical output options – these values are analysis values that you want to be transferred from the analysis software to Tekla. The application of these values will be explored in the next section where Open API may be used for additional engineering design such as design of connections, trusses, and concrete reinforcement.

12.) Run preliminary structural analysis for member sizes. Check if analyzed members sizes are the same as design sizes. If not, send new sizes back to Tekla.

13.) Create drawings with plans, sections, and details. Modify member sizes as necessary for detail purposes. Re-run structural analysis to check adequacy and effects on structural stability.

14.) Use "Export to Revit" add-on to send IFC structural model to architect.

15.) Receive updated architectural IFCzip files. Use 'change detection' in reference model properties dialog box and manually update the Tekla model. As an alternative, use the new "IFC Change Management Extension" available on Tekla's Extranet as an add-on to review any changes made and automatically update the Tekla model with the changes. Update analysis model as necessary.

16.) Re-run structural analysis. Update structural element member sizes and connection designs as necessary.

17.) Repeat steps 9 through 15 throughout the project design phase.

18.) Use clash detection to check for clashes between structural elements and architectural/MEP reference models.

19.) Use structural analysis model outputs to design beam and girder connections, column splices, column baseplates, foundation elements, floor systems, and lateral bracing. Utilize Open API spreadsheets and programs to automate common or repetitive designs. Examples include the “Design by Excel” option for connections.

20.) Create 2D drawings to properly document all plans, elevations, schedules, and details. During this transition period where the technology of BIM is still being tested for fidelity and longevity (both necessities in the construction industry), the creation of proper 2D documentation is still required. The scope of proper drawing production is beyond the scope of this thesis but worth exploring as an integral portion of the holistic BIM workflow.

Conclusions and Recommendations

The responsibility of the structural engineer is the design and analysis of the structural system of a project. But this is only half of the work – the other half is creating the construction documents that are used during construction. The famous phrase, "The devil is in the details" is particularly applicable here as the details may change or even dictate the structural design.

Another concept that is needs addressing is one of legal liability. When elements are being shared and models are being combined, who takes responsibility for changes or decisions made using their models? How do you define what objects/elements/properties/measurements take precedence in a three-dimensional model?

What about companies that spend time and resources developing custom elements, connections, and objects? Most companies do not share trade secrets and the open sharing of BIM models results in the transfer of valuable information. This concept is known as "selfish BIM" where open-source development is not profitable and proprietary progress becomes important. There are workarounds to directly sharing BIM data with the use of three-dimensional PDFs or sharing objects via readers such as Tekla's BIMsight software. This does not resolve the issue completely as the full usefulness in BIM is limited without the sharing of full-access BIM models.

One other issue that requires further study is the technical limitations of modeling software. Tekla only recently introduced the conversion of planar elements such as walls and floors into native Tekla elements. The conversion progress is far from perfect and does not properly import many objects just as concrete slab on metal deck or waffle slabs. API can be developed to properly model objects such seismically dampened braces, waffle slabs, or concrete-encased wide-flange beams.

An issue with using Tekla in a BIM workflow is the fact that there are many different types of objects that does not have a native Tekla object. Tekla's objects are all structural objects but having

Lastly, as with any new technology, there is a lack of industry-wide standards. Although standards in CAD design were only developed at company and local government levels and never achieved industry standards, some degree of standardization is important for BIM. Building Information Model standards vary greatly in quality, consistency, and data format. The buildingSMART alliance project committee "National Building Information Model Standard Project Committee - United States" also known as NBIMS released a free-to-the-public "National Building Information Model Standard" (available at http://www.buildingsmartalliance.org/index.php/standards/) which describes at length the importance of BIM to the industry as well as the goals of BIM standards.

APPENDICES

APPENDIX A – SOFTWARE

1.) Tekla© Structures 16.1 Service Release 1 (Build 627153)
    - 'Export to Revit' add-on application
    - IFCConverter Macro
2.) Tekla© Structures 17.0 Service Release 1 (released April 19th, 2011)
3.) Tekla© Structures 17.0 Service Release 3
4.) Tekla© BIMSight Version 1.2.1
5.) Autodesk© Revit Structure 2011
    - 'Export to Tekla' add-on application
6.) Autodesk© AutoCAD 2011 – Educational Version
7.) CSI© SAP2000 Version 14
8.) Microsoft© Excel 2010

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