

VIRTUAL STEEL MODEL CONCEPT FOR INFORMATION AND FABRICATION INTEGRATION

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ABSTRACT

This paper discusses reported problems related to the lack of communication between engineers and fabricators of steel structures using documented examples and provides alternative solutions as expected through the use of a virtual steel model concept. Significant improvements in communication between all participants (architects, engineers, technicians, draftsmen and fabricators) and particularly between the engineers and fabricators are expected in areas such as connection design, bracing connections and end preparations. The participation of every team member is enhanced because of a better understanding of the structural model, precise definition of forces, relevant structural details and fabricators preferences. The guesswork of defining the actual loads for connections and conservative transfer forces and brace forces for bracing connections are eliminated for the benefits of a safe and economic structure in addition to a better understanding between all participants.

KEY WORDS

steel construction industry, software integration, information technology, virtual model.

INTRODUCTION

This is the second part of a series of papers to be presented by the authors in an attempt to analyze some complex problems in the construction industry and to pave the road for innovative solution concepts in the steel industry. The reader is invited to read the first part (Elmaraghy and Bauer 2005) to better understand the points of view for possible remedies using Information Technologies (IT) to the problem of low productivity in the construction industry.

It has been stated that professional construction organizations face an extremely competitive market where firms that apply technology-driven packages seem to be gaining a sustainable advantage, mainly in the form of more accurate and effective cost estimating, better coordinated designs and spatial visualization of the final product, as well as improved project communications and minimized errors and omissions.

This paper will further explain some of the concepts of the 3D virtual steel model to solve existing problems in the steel industry and demonstrate the results with the help of existing technology namely the Virtual Steel Buildings™ (VSB).

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Specific technology is needed to offer to all participants such as architects, engineers, detailers, fabricators, managers and others, the various and related configurable views to address their respective working tasks priorities while eliminating the guesswork and improving communications with all other participants on the project. In our opinion, any successful implementation of steel technology needs to start as early as possible, that is, at the engineering level conceptual design. This will result in better communications between the fields of engineering design and detailing and the fabrication and erection for safe and economic steel structures.

COST-EFFECTIVE STEEL BUILDING DESIGN

Carter et al. (2000) have provided statistical summary information related to cost and the findings clearly confirm that least weight steel design does not mean least steel project cost for the owner. The material cost category includes structural shapes, plates, joists, decks, bolts, welds, paints, and waste material. The material cost has dropped from 40% of the total cost in 1983 to 26% in 1998. The fabrication labor cost category includes the fabrication labor required to prepare and assemble the shop assemblies of structural steel, plates, bolts, welds and other materials and products for shipment and subsequent erection in the field. The fabrication cost has increased slightly from 30% of the total cost in 1983 to 33% in 1998. The erection labor cost category includes the erection labor required to unload, lift, place and connect the components of the steel frame. This cost has increased from 19% of the total cost in 1983 to 27% in 1998. The other cost category includes all cost items not specifically included in the three foregoing categories, including outside services, shop drawings and the additional costs associated with risk. The cost in this category has slightly increased from 11% of the total cost in 1983 to 13% in 1998.

For a typical structural steel building, materials cost about 25% and other costs amount to 15%. The largest share is related to fabrication labor cost (35%) and erection labor cost (25%). The combined fabrication and erection cost of 60% will lead us to concentrate all efforts to propose feasible technological concepts and solutions to reduce the share of both fabrication and erection cost.

MEMBERS END PREPARATIONS AND COPINGS

Copes, blocks, cuts and clips can significantly reduce the design strength of members and may require web reinforcement. Often it may be more economical to use a heavier member than to provide such reinforcement and perform costly material removal operations. When the strength of a coped beam is inadequate, reinforcement can be added but appreciable labor cost is associated with stiffeners and/or doubler plates. Also, several limit states must be verified according to the various code specifications.

Unusually long and deep copes and blocks, or blocks in beams with thin webs, may materially affect the capacity of the beam. Two situations have been cited by Milek (1980) as examples in which deep copes may render invalid the initial assumptions for the design of the main member. The first situation refers to a cope introduced into the end panel of a plate girder. Depending upon the size of the cope, reinforcement of the web panel is required or at least support to the web along the coped edge that provides adequate restraint against out-of-

plane buckling. The second situation is related to theoretical formulas for laterally unbraced beams, which assume that the beam is restrained in an upright position at the point of support. A laterally unsupported beam with long or deep copes, especially with both flanges coped, would be elastically restrained rather than rigidly restrained. Torsional strength and stiffness of the coped section will control the resistance of overturning.

For a laterally unbraced beam with top flange loading, localized distortion and twisting of the cross section within coped region may occur and must be verified. For all other loads, the lateral strength of the beam as a whole need to be verified according to the applicable specifications and accounting for the beam end preparations and added reinforcements.

Reinforcement of the member ends with web doublers and/or stiffeners is a costly intervention that could be avoided if the structural engineer is aware of this and can change the member size prior to releasing the design drawings. In a real structure, the end preparation details can be extensive, time consuming and elaborate. It will generally be an obstacle for many structural engineers while considered to be as a common task for detailers. Some engineers are told that end preparation and connections are a detailing issue that is best left to the expertise of the fabricator. The structural engineer who is asked to verify the strength of all beams and girders accounting for end preparation will be greatly helped by an automated technology that can provide the location, type and shape of the most applicable end preparations geometry. The limit states required to be checked according to applicable code provisions for end preparations can not be achieved without the detailed geometries.

Advanced mathematical formulations related to docking of 3D objects in space together with a large set of applicable rules derived from the domain of detailing will provide the fundamental characteristic of the Virtual Steel Buildings™ model (SAFI 2006). The 3D space model (Figure 1) initially defines the configuration and geometry for the member end preparations. Figure 2 shows coping samples achieved through the use of this technology, seen within the virtual 3D solid mode, as extracted from a general 3D structure where beams and columns are oriented in space in any possible angle. Columns can be canted, and beams cardinal points, flange and web angles are arbitrary in the 3D space. Any possible spatial interaction can be obtained between available commercial steel sections.

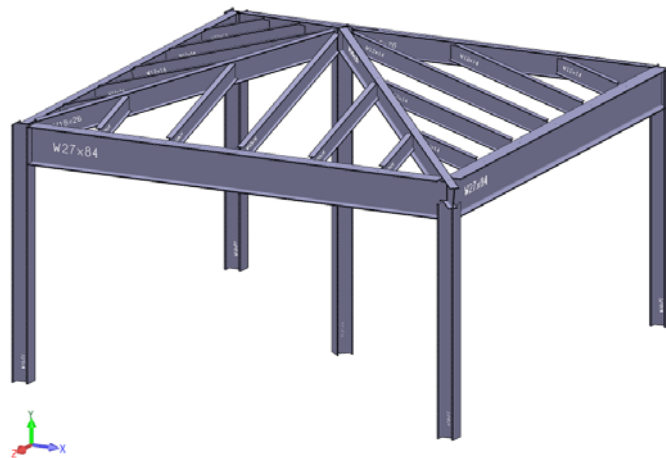


Figure 1: Virtual Steel Buildings™ Model (VSB Model)

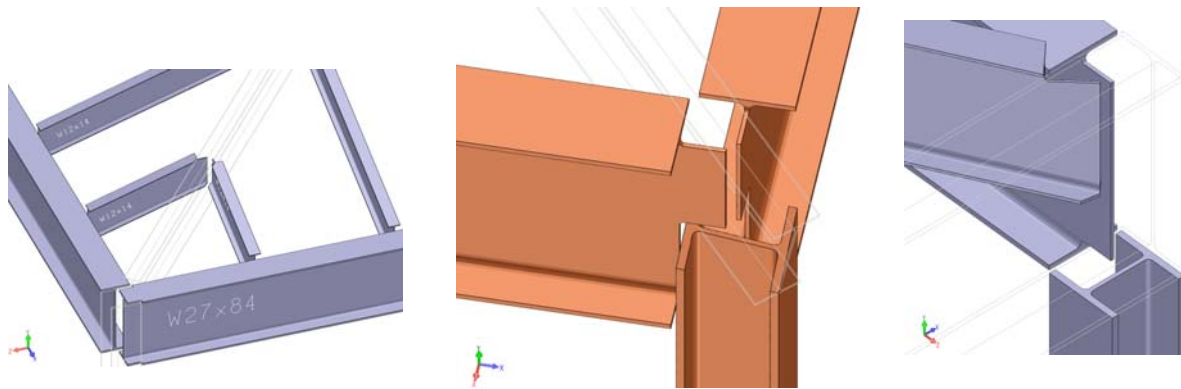


Figure 2: Samples of Members End Preparations

Extensive editing features (Figure 3) are provided for all geometrical configurations that permit the modification of the coped dimensions. Changing the applicable type of end preparations, when feasible from a detailing point of view, is also possible. Furthermore, limit states applicable to coped members with various end preparations are automatically checked.

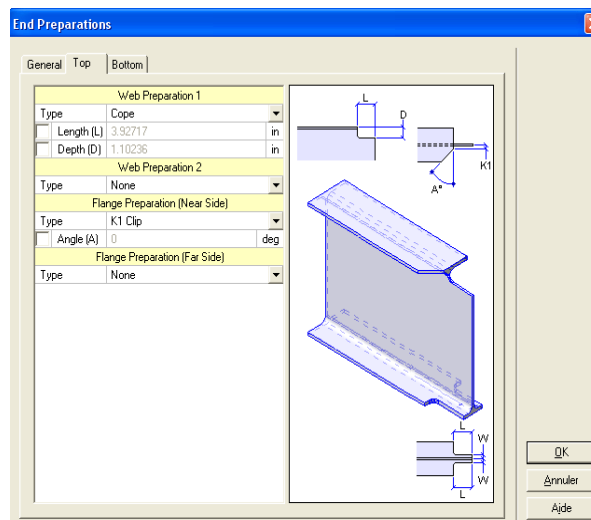


Figure 3: Sample of Dynamic End Preparation Editing Features

The engineer will continue to work in the traditional engineering mode using the VSB model, as he always worked with conventional structural software programs. Structural limit states verifications will be applied to the main members of the structure and to all members end preparations. At any time during the analysis and design cycle, the user can switch modes instantaneously between the various configurable views. From the engineering mode, which is essentially a 3D frame wire mesh (Figure 4a), switching to the 3D solid virtual mode will highlight all virtual members with members connectivity, end preparations, connections and full bracings (Figure 4b). Switching to the detailing mode will permit printing the automated floor plan view and detail drawings to AutoCad and other CAD software (Figure 5).

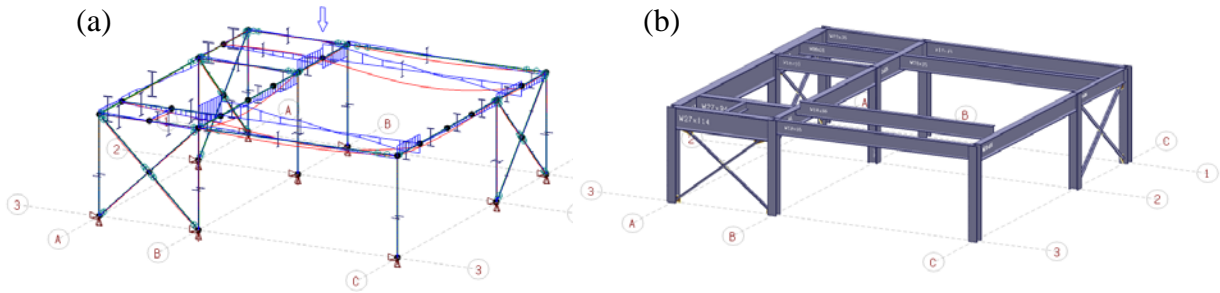


Figure 4: (a) Engineering Wire Frame Model/ Engineering Mode; (b) Virtual Steel Building 3D Solid Model/Virtual Steel Mode

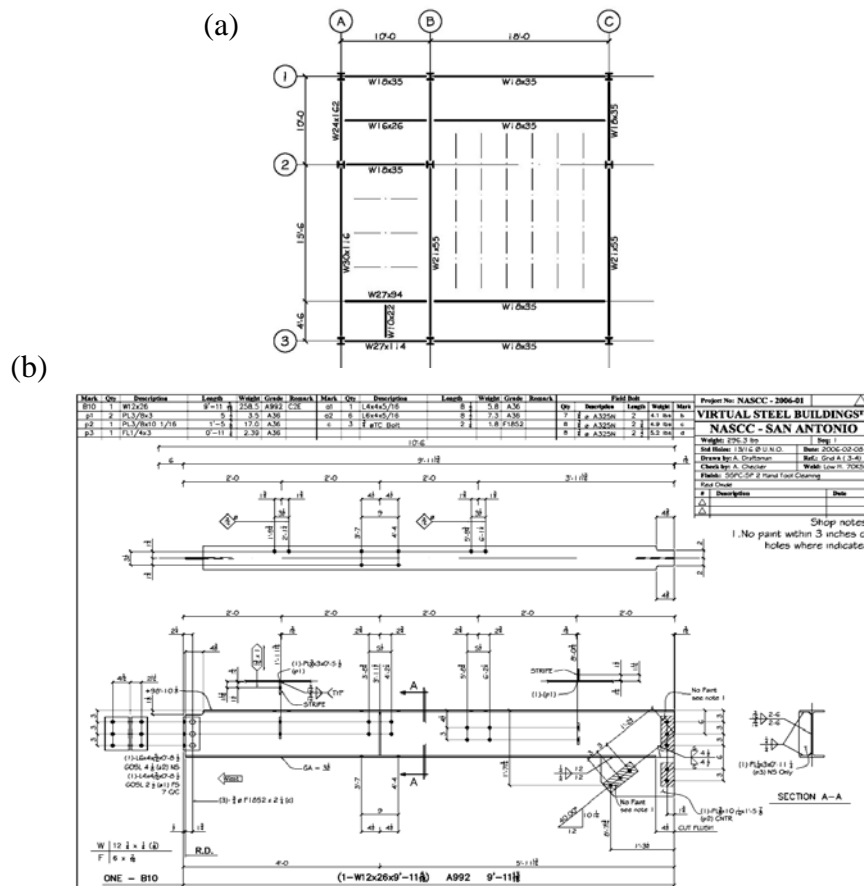


Figure 5: (a) Floor Plan View AutoCad Generated Drawing/from the Detailing Mode; (b) Detail Drawing/from the Detailing Mode

The provided default preferences or the fabricators preferences, which affect the choice of end preparations and connections design, are recorded in a unique database. While the structural engineer is processing his interactive analysis and iterative design cycles within the engineering mode, all information regarding the end preparations and connections are immediately available in the virtual and connections modes.

While the principal components in a steel building are the structural members and the connections that hold the members together, members end preparations are in our opinion the root of the complex steel economy equation. Details defined early at the engineering design stage will have a significant influence on all subsequent operations and on the final cost of the project.

ENGINEERING MODEL

With the widespread use of structural software with optimization capabilities and with the limited training received early at the undergraduate level (Green et al. 2002), it is common to find structural design engineers in practice targeting the objective of minimum weight for every member of the structure instead of grouping the members in practical manners. This approach may often result in uneconomical steel connections design and expensive reinforcement fabrication and erection cost.

Structural failures occur often due to connection deficiencies emanating from a lack of understanding of the many applicable connections limit states in addition to those applicable to main structural members. The designer needs to know what limit states are applicable to a particular connection where changes in details may drastically influence the performance of a connection. The VSB model provides all details related to the connections limit states according to AISC (2005) and allows the engineer to modify any given parameter and assess its influence on the design (Figure 6).

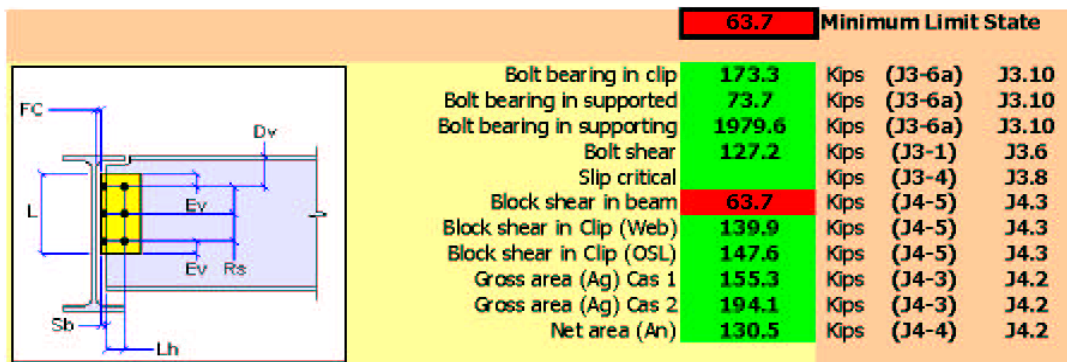


Figure 6: Sample Connection and AISC Limit States from the VSB Model

The virtual steel model has been developed in order to assist the design engineer with the help of a working environment controlled by a number of configurable views. For the design of the structure, the engineering mode (Figure 4a), is the conventional and appropriate choice. Members and bracings are still represented as wire frame elements connected as usual to the frame grid joints. End node releases and supports are also represented in the usual manner.

The 3D solid model can be visualized in the virtual mode configurable view, by simply switching from the engineering mode to the virtual mode in flip of a second (Figure 4b). The whole structure is presented in 3D as a real life scenario including beams, columns, girders, member end preparations such as copings, blocks, cuts and clips. Lateral and vertical bracing systems of various types are automatically generated, including gusset plates and connection

material such as plates, angles, tees and other detail pieces joined by bolts and welds (Figure 7).

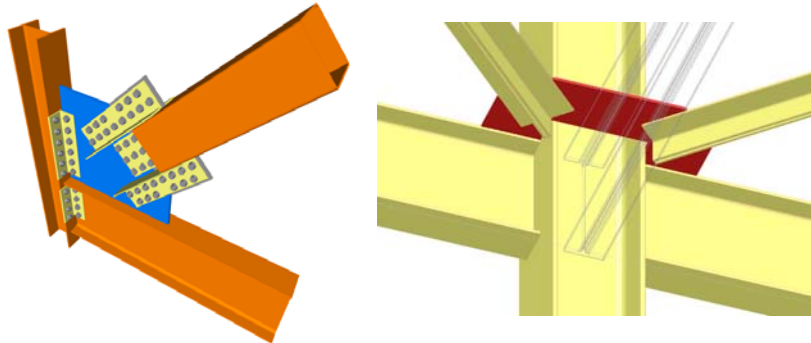


Figure 7: Vertical and Horizontal Bracing Systems from the VSB Model

The model parameters can be edited at any level while navigating in the engineering and other modes. Since the model is unique, editing action is needed only once for any parameter. Some parameters are best edited in the mode where they are clearly represented.

All actual loads and transfer forces generated by the engineering model are directly available at connection joints and bracings (Figure 8). There is no need for transfer of loads between different foreign environments through a data exchange protocol or from external sources. The actual loads are used to define the load path and magnitudes at all individual plies of material composing the connections and at the individual fasteners and welds. The design of connections is performed for every applicable limit states following the appropriate specifications and using the actual loads, thus ensuring safety and economy (Thornton 2003).

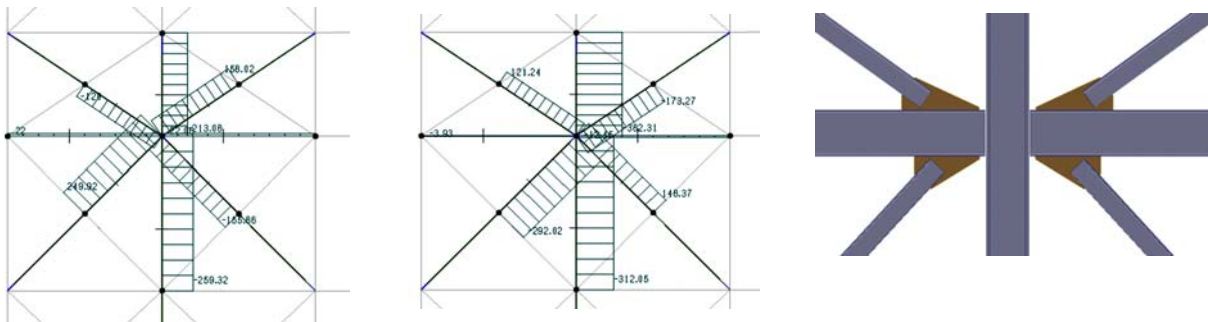


Figure 8: Bracing Engineering Model (Load Combinations 1 and 2) and VSB Mode

SHEAR CONNECTION DESIGN

In most cases, structural jobs specify the beam shear load indirectly by referring to one of the following instructions on the contract documents: full depth connection, all shear connections shall contain the maximum possible number of rows of bolts; design all shear connections for $\frac{1}{2}$ UDL; design all shear connections for the shear capacity of the beam; minimum design loads for standard rolled shapes, unless noted otherwise: W8 - 10 kips; W10 - 15 kips, etc.

Despite the existence of structural software technology, the communication channels do not transfer the actual shear loads in the original design to the fabricator without guesswork. The beams are sized, the shear information is available but it does not flow in a seamless manner. Room for errors can take place and frustrating communication arises between the fabricator and the engineer (Thornton 2003).

In the following, comparisons will be made between connection configurations obtained using the instructions mentioned above and those obtained using the actual beam end shear loads. The model studied, shown in Figures 4 and 5, was created with the VSB technology.

FULL DEPTH CONNECTION, ALL SHEAR CONNECTIONS SHALL CONTAIN THE MAXIMUM POSSIBLE NUMBER OF ROWS OF BOLTS

This instruction implies that the engineer intends to exceed all combined loads and limit states. Consider the W16x26 beam with a cope (Figure 9a). By verifying the LRFD design table (AISC 2006), the reduced shear capacity is 63.7 kips, which is 95 % of the full beam shear capacity. Figure 6 shows detailed results for all limit states of the coped beam from the VSB model. It can be seen that the shear capacity of 63.7 kips results from the “Block shear in beam”. All other limit states are tabulated leading to a better understanding by the engineer of the behavior of the various connection parameters.

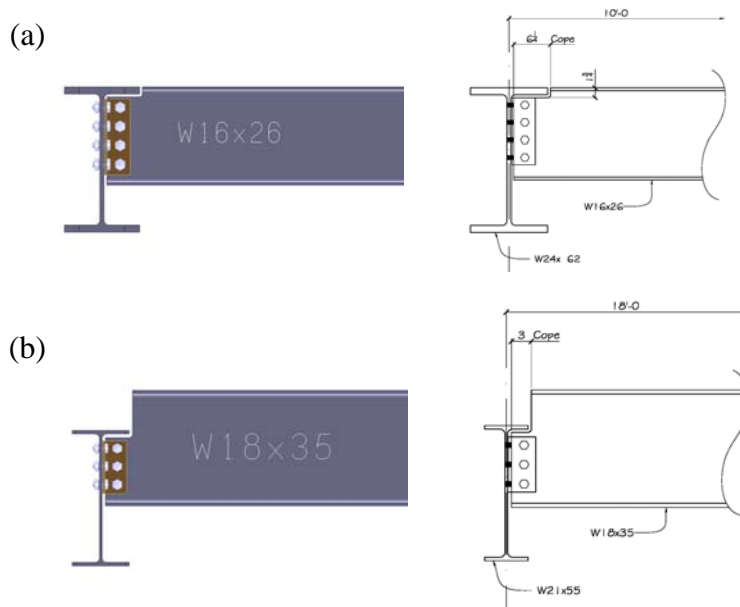


Figure 9: (a) Supported Coped Beam W16x26; (b) Supported Coped Beam W18x35

A more severe situation can occur where the top steel of two beams are at different elevations (Figure 9b). For the W18x35 supported beam, the full depth connection from LRFD is 49.9 kips. However, this specific configuration results in a beam shear capacity of only 18.6 kips (37% of required) as controlled by the “Bolt bearing in supported” limit state.

In most cases, the engineer is not aware of the fabricator final configuration and end preparations. The common assumptions can be very costly to repair after fabrication and

erection of an unsafe structure. Starting from given coping dimensions, it is impossible to develop the shear capacity required to sustain standard connections such as single clip, double clip, shear end plate, shear tab without the addition of expensive web doublers.

With the VSB technology, the engineer works in the engineering mode and, once his preliminary design is done, he can switch to other relevant configurable modes, explore the resulting end preparations, and check the true shear capacity of the beam and the connection design results with all limit states calculated using the real load cases. Hence, communication problems reported by Thornton (2003) will be resolved with the adequate use of tools and technology.

DESIGN ALL SHEAR CONNECTIONS FOR 1/2 UDL

The UDL method can be uneconomic for in-fill beams near the ends of a main beam (Thornton 2003). Consider the short, 4 ft 6 in long, W10x22 beam framing between the W27x114 and W27x94 beams. The 1/2 UDL reaction is 87 kips and the resulting connections are shown in Figure 10a. Also, the beam shear capacity is 66.1 kips and requires connections as shown in Figure 10b. These connections are uneconomic and probably unjustified. In fact, the shear force diagram of Figure 4a indicates a shear reaction of about 2 kips. For such a load, an appropriate shear connection which develops 6 kips consists of a double clip angle with two bolts (Figure 10c).

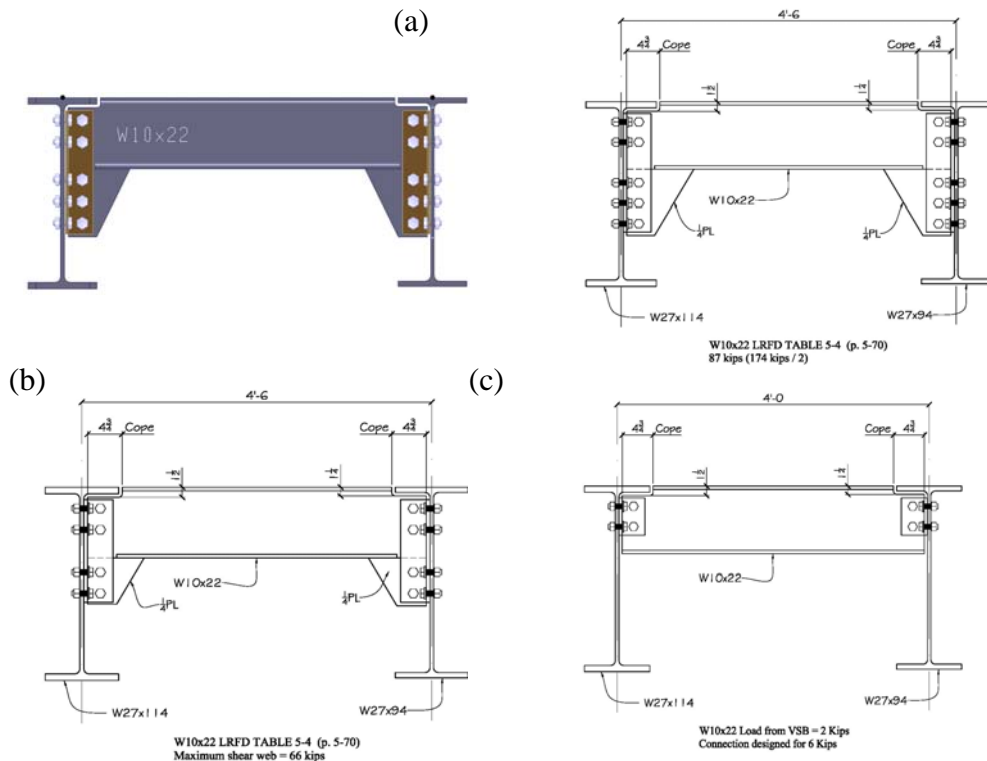


Figure 10: (a) In-Fill Beam Shear Connection Based on 1/2 UDL; (b) In-Fill Beam Shear Connection Based on Beam Shear Capacity; (c) In-Fill Beam Shear Connection Required

DESIGN ALL SHEAR CONNECTIONS FOR THE SHEAR CAPACITY OF THE BEAM

The previous examples demonstrated that if this statement is added to the contract documents, an uneconomical design may result as for beam W10x22 (Figure 10b) or an unsafe design as for beam W18x35 (Figure 9b).

Thornton (2003) comes to the conclusion that there is no substitute for giving the actual loads when considering both safety and economy. We agree fully with such findings. The configurable views of the VSB technology will offer the engineers and detailers an immediate access to all relevant information for an accurate investigation and the possibility of editing the design and the geometrical parameters for further explorations.

BRACING CONNECTIONS

Thornton (2003) cited a real case where the fabricator has been forced to deduce the connection interface forces or transfer forces. The fabricator analysis based on simultaneous and non simultaneous loads resulted in a range of forces varying from 23 kips to 223 kips. For safe design the fabricator had to use 223 kips. The actual transfer forces finally provided by the engineer was 30 kips. Transfer forces ambiguity, lack of clarity in communications through data exchanges or drawings can lead to a design based on ignorance rather than on knowledge.

For the vertical bracing system shown in Figure 8, the engineering mode displays loads for two load combinations and the 3D solid mode displays the bracing gussets attached to the beams. All end preparations, gusset geometry and attachments are provided in the solid 3D virtual mode and the transfer of forces at connection joints can be immediately obtained. If only the maximum axial forces were communicated, the fabricator could only deduce that the horizontal force to be transferred from the beam end connections to the column ranges between ± 33 kips in the best case and ± 307 kips in the worse case. With the VSB technology, the engineer and the fabricator know immediately that the maximum transfer force for both load combinations is equal to 110 kips.

CONCLUSIONS

Steel projects economy is maximized when the design simplifies the labor associated with fabrication and erection. Member end preparations are the root of the complex steel economy equation and the focal point for any successful virtual steel model concept. Copes, blocks, cuts and clips often reduce the design strengths of members and may require expensive web reinforcement. The structural engineer of record should be aware of these situations before releasing the design drawings to the fabricator.

The structural engineer who is asked to verify the strength of the structural model beams and girders accounting for end preparations will be greatly helped by an automated technology that provides the location, type and shape of the most applicable end preparations. The limit states required to be checked according to applicable code provisions for end preparations and connections can now be achieved with precision and without guesswork with the help of the VSB technology.

The ultimate responsibility for the design of the connections in a structure is with the structural engineer of record. As for member end preparations, connection design needs to be

an essential part of the structural engineer design task and instead of optimizing the structure only for weight, it is more economical to optimize the whole structure on the basis of connections requirements.

For those who believe that there is no substitute for giving the actual loads when considering both safety and economy of connections and bracings, the current VSB technology provides all actual loads and transfer forces generated by the engineering model directly at connection joints and bracings.

The VSB technology possesses a number of configurable views including the conventional engineering mode, the 3D solid virtual mode, the connection mode, the detailing and fabrication modes and others to be added. Switching between these interrelated configurable view modes is as easy as switching TV channels with a remote control.

ACKNOWLEDGMENTS

The authors would like to thank SAFI Quality Software Inc. for supplying information on the Virtual Steel Buildings™.

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