ON MODELING ROOF COMPONENTS AND THEIR EFFECT ON THE BEHAVIOR OF THE PRIMARY STRUCTURAL SYSTEM OF AN INDUSTRIAL STEEL BUILDING

Souhail Elhouar[1] and Murad Hamdallah [2]

ABSTRACT

Traditionally, structural steel industrial buildings are designed to resist lateral loads using moment frames in the transverse direction and a bracing system in the longitudinal direction. In the latter case, the braces are designed to accomplish two goals: 1) provide sufficient lateral support for the gravity load supporting system, and 2) resist all the lateral loads that may be applied in the longitudinal direction of the building. No consideration is typically given to the possible contribution of the panel/purlin system except that they are assumed to form a rigid diaphragm to transfer forces from the structure to the bracing system. Theoretically, such a structure is unstable in the longitudinal direction if the braces are removed. In reality, however, some stiffness is usually provided by the attachment of secondary structural members such as roof purlins and deck panels.

This study proposes a methodology by which a complete structural system, consisting of the rigid frames, roof purlins, and deck panels, with or without a bracing system, can be modeled using simple line elements, to assess the magnitude of the longitudinal deformation of the system under the effect of a given lateral load. To accomplish this, it was necessary to study and model the behavior of each individual component and its interaction with other components, and then integrate the individual models to produce an overall model for the complete structure. The study showed that the interaction between primary and secondary structural components can be modeled, and that the obtained model can give consistent and meaningful results.

KEY WORDS

modeling, longitudinal stiffness, steel building, roof purlins, roof panels

INTRODUCTION

In a braced frame such as the one shown in Figure 1, the braces are typically designed to accomplish two goals: first, to provide sufficient lateral support for the gravity load supporting system, and second, to resist all the lateral loads that may be applied in the longitudinal direction of the frame. As shown in the figure, this frame is typically modeled using simple beam-to-column connections that do not allow for the transfer of moments between the different components. No consideration is typically given to the possible

[1] Assistant Professor, Dept. of Civil Engineering and Construction, Bradley University, 1501 W. Bradley Avenue, Peoria, IL 61625, USA, Phone 309/677-3830, FAX 309/677-2867, selhouar@bradley.edu

[2] Project Engineer, A. Lucas & Sons Steel, 1328 S.W. Washington St. Peoria, IL 61602, USA, Phone 309/673-8547, FAX 309/673 7213, murad@alucasandsons.com

contribution the panel/purlin roof system other than that it is assumed to form a rigid diaphragm that helps transfer lateral forces from the structure to the bracing system.

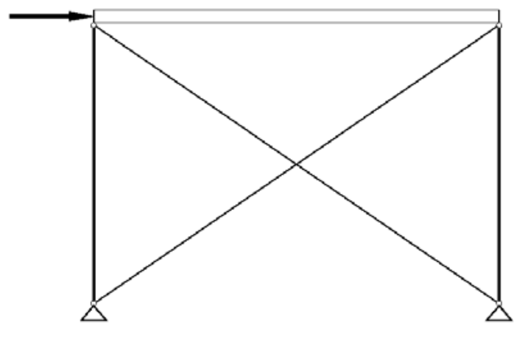

Figure 1: Typical Analysis Model of a Braced Frame with a Rigid Roof Diaphragm

This approach works well for design purposes because the contribution of secondary components towards the lateral force carrying capacity of the structure is expected to be negligible when compared to that of the bracing system. Therefore, and from a theoretical point of view, removing the braces will cause the structure to become unstable and incapable of carrying any of the applied loads, as depicted in Figure 2.

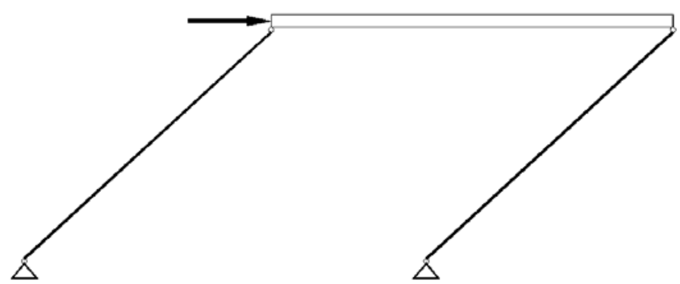

Figure 2: Simple Frame Behavior under Load when Braces are Removed

In reality, however, inherent connection stiffness and the stiffness of roof system components may provide some degree of lateral resistance. This resistance may prevent large deformation from taking place in the structure, at least until a substantial lateral force is applied. In fact, the structure may behave more as per the model shown in Figure 3, in which the simple roof to column connections have been replaced by rotational springs that derive their stiffness from panel-to-purlin and purlin-to-rafter attachments, thus making a small contribution towards the stiffness of the system as a whole. However, there has never been an attempt reported to evaluate the extent of this contribution. This may be due to the inhibitive cost that would be associated with an experimental program to investigate it, and also to the difficulty involved in developing a computer model that would accurately reproduce the behavior of the roof system components and their interaction with each other. Nevertheless, recent advances in structural analysis software have made it possible to model and study the behavior of complex structural systems and assemblies with reasonable effort and accuracy. The objective of the study being reported herein is to develop a methodology for producing three-dimensional models to simulate the longitudinal behavior of a typical steel-framed industrial building. This involves the modeling of the steel frame and its interaction with the various secondary structural components, namely, the purlins, panels, and braces. This methodology can then be used to study the contribution of the panels and purlins to the system's ability to resist lateral forces in the longitudinal direction. More importantly, the methodology will make it possible to study the behavior of secondary structural components in a simulated realistic environment, which may lead to better component design and performance.

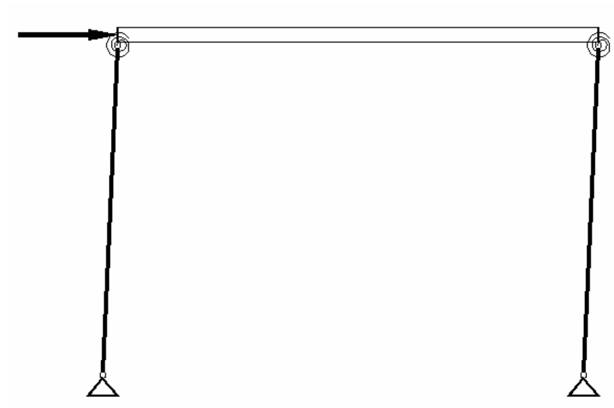

Figure 3: Rotational Spring Representation of Roof-to-Column Connection

REVIEW OF LITERATURE

Although three dimensional computer modeling of structural systems has been around for many years, little has been done in attempting to model the interaction between primary structural systems and secondary structural or building components. This is especially the case where industrial steel structures are concerned. This is probably due to many reasons, of which the following three are identified:

1. the lack of a perception of evidence for tangible practical impact on the industry that would result from such an attempt,
2. the difficulty involved in modeling the interaction between the different structural and non-structural components, and
3. the prohibitive cost of validating computer models using full scale or model tests of the structural system being considered.

However, three dimensional modeling of structural systems and other components has been attempted in other industries where the aforementioned reasons are either non applicable or their effects are minimized. Two of such industries are the post-frame building and metal framing industries, and a comprehensive synthesis of their research programs and findings was conducted by Hamdallah (2005).

Research in the post frame building industry has traditionally dealt with two main issues: the investigation of roof and wall panel stiffness and its effect on structural behavior, and the testing and modeling of full scale building systems, mainly to examine the behavior of posts and rafters in a typical setting. Many studies have been conducted in an effort to define the stiffness of roof diaphragm panels, and procedures for diaphragm design in metal-clad post-frame buildings have been developed. In particular researchers (e.g., Nilson A.H. 1960, McFadden and Bundy 1991) studied and compared methods for evaluating diaphragm shear stiffness. Their work was instrumental in setting up the stage for the modeling and testing of complete post-frame building systems to evaluate their overall stiffness and behavior.

The metal building industry has also shown a great interest in studying roof panel systems and assessing their behavior. Elhouar (1985) developed a stiffness model to estimate brace forces in cold-formed Z- and C-purlin supported roof systems. He was able to model the interaction between the roof deck panels, purlins, and bracing system and obtained accurate predictions of brace force and purlin deformation. The equations he developed are still being used today in the AISI Cold Formed Steel Design Manual (1996) to predict bracing requirements for multiple-span, multiple-purlin line roof systems using cold-formed steel shapes.

Other researchers studied panel-purlin interaction using the finite strip method (e.g. Polyzois and Guillory 1991) or an elasto-plastic finite element model (Lucas, Al-Bermani, and Kitipornchai 1997), but, up to the time of publication of this study, there have been no reports of any attempts to study the interaction between the main structural system of an industrial steel building and secondary roof components using a three-dimensional model. The next few sections describe the approach that these authors used to accomplish this task, and an analysis of the findings is presented at the end of the paper.

ANALYTICAL MODEL DEVELOPMENT AND PARAMETRIC STUDY

An efficient three-dimensional modeling of a structural system must pay special attention to the interaction between the various components. For the particular case of an industrial steel building; the model must be able to accurately reproduce the behavior of the actual structure in terms of forces and displacements. This can only be possible if structural components and their interaction with each other are modeled correctly. In other words, the model must represent the primary structural members, i.e. columns and beams, the secondary structural members, i.e. purlins and girts, braces, claddings: i.e. roof and wall panels, and their connections in such a way that estimated forces and displacements are representative of what may be observed in the actual structure. Effective modeling of primary structural system components can easily be achieved using the stiffness method and obtained results usually correlate well with experimental data. However, modeling the interaction of claddings and secondary structural members with the main members is still a tricky endeavor.

MODELLING THE ROOF DIAPHRAGM

Considering the fact that diaphragm shear stiffness can play a big role in the behavior of a structure, a decision was made to start the study by modeling a roof diaphragm test setup and then calibrating it using published diaphragm stiffness data before integrating it into the overall model of the building structure. Two modeling approaches were evaluated. In the first, deck panels were modeled using analysis program generated finite elements. This approach did not yield a good correlation between estimated results and published data. The second approach involved the use of a truss-like arrangement to represent deck panels. As may be seen in Figure 4, the diaphragm was modeled using three types of line elements: longitudinal rods directed along the deck span, transverse rods directed along the purlins, and diagonal rods to provide shear stability and stiffness to the model in the plane of the panel deck. All of these members are attached to the top nodes of the dummy members, which are created at the frequency of three members per purlin. The dummy members are provided to ensure the compatibility of displacement between the tops of the purlins and the roof deck they are attached to. This approach worked well and the model was satisfactorily calibrated to yield accurate results. Subsequently, a technique for estimating the moment-rotation relationship at ends of roof panel supporting purlins was introduced. This technique makes use of the following assumptions: 1) small deformation theory applies, 2) the panel deck material remains elastic (i.e. no yielding will occur in the deck), 3) the purlin is simply supported by the rafter with the attachment coinciding with the purlin's centerline, and 4) the portion of the deck panel that spans over the ends of the purlins is flat and secured by a fastener on each purlin.

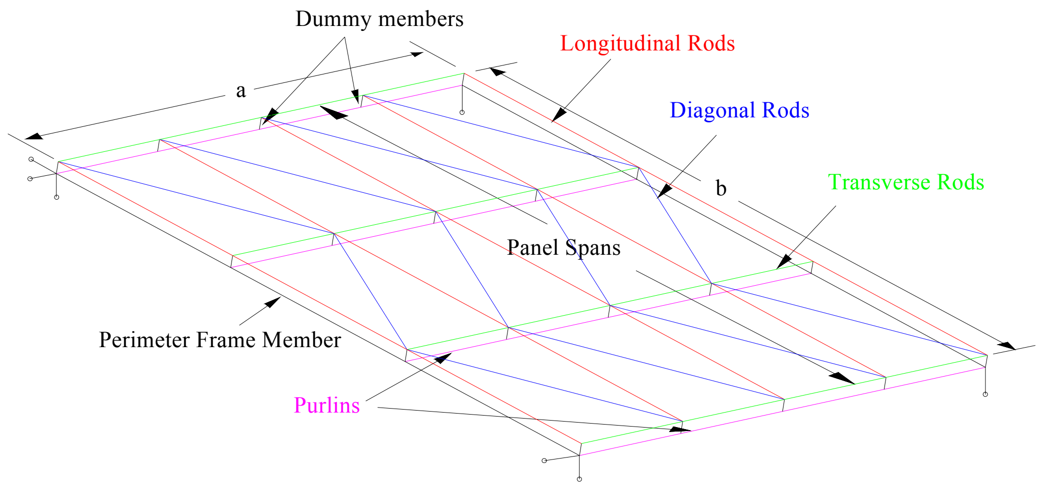

Figure 4: Equivalent Truss Diaphragm Model (Figure 3.11 in Hamdallah 2005)

INTEGRATION OF THE ROOF MODEL INTO THE OVERALL STRUCTURAL MODEL

The developed roof model was then placed on an industrial steel building model that was designed for the purpose of the study. Three different purlin-to-rafter connection configurations where considered in this model. In the first configuration, the purlins were pinned at both ends, which means that they could not carry any moment across the bays of the building. In the second configuration, the purlins were partially released at their ends with respect to their strong axes. And in the third configuration, the purlins were fully restrained at their ends. Analyses were then performed to see if the interaction between primary framing members (beams, columns, and braces) and secondary framing members (purlins and deck panels) was adequately represented. The structure was analyzed in one, two, three, four, and five-bay configurations using purlins with braces only, purlins with deck panels only, and purlins with braces and deck panels. Figure 5 shows a depiction of a one-bay version of the model with all components present.

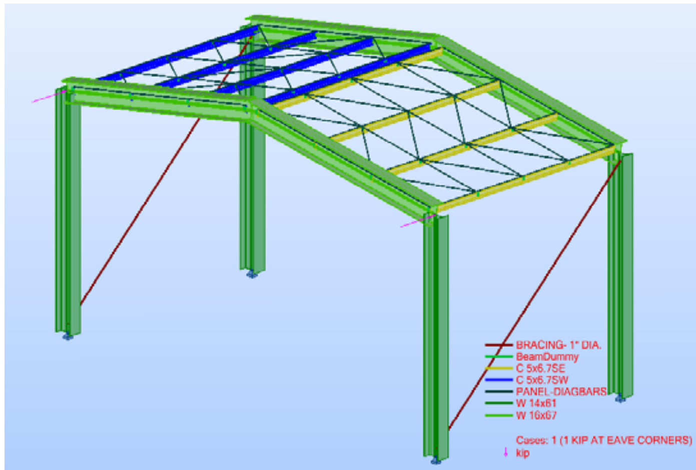

Figure 5: One-Bay Gable Roof Structural Model (Figure 4.1 in Hamdallah 2005)

Two 1-kip horizontal concentrated loads were applied at the eaves of one frame at the level of the connection the rafter and the column as shown in the figure. Deflections are then noted for the three longitudinal bracing configurations. The results of the analyses are shown here in Table 1 through Table 3 for the various purlin end-restraint configurations that were considered.

Table 1: One Bay Longitudinal Deflection When Using Pinned Purlins
(Table 4.1 in Hamdallah 2005)

Run No.	Case Description	Eave Node No.	Transverse Disp. ΔX (in)	Longitudinal Disp. ΔY (in)	Vertical Disp. ΔZ (in)
1	Bracing attached	7	0	0.0258	-0.0003
	No Panel attached	10	0	0.0258	-0.0003
2	No Bracing attached	7	0.0002	15.8752	-0.0003
	Panel attached	10	-0.0002	15.8752	-0.0003
3	Bracing attached	7	0	0.0255	-0.0003
	Panel attached	10	0	0.0255	-0.0003

Table 2: One Bay Longitudinal Deflections When Using Partially-Restrained Purlins (Table 4.2 in Hamdallah 2005)

Run No.	Case Description	Eave Node No.	Transverse Disp. ΔX (in)	Longitudinal Disp. ΔY (in)	Vertical Disp. ΔZ (in)
1	Bracing attached No Panel attached	7	0	0.0257	-0.0003
		10	0	0.0257	-0.0003
2	No Bracing attached Panel attached	7	0	9.2534	-0.0003
		10	0	9.2534	-0.0003
3	Bracing attached Panel attached	7	0	0.0249	-0.0003
		10	0	0.0249	-0.0003

Table 3: One Bay Longitudinal Deflections When Using Fully-Restrained Purlins (Table 4.3 in Hamdallah 2005)

Run No.	Case 1	Eave Node No.	Transverse Disp. ΔX (in)	Longitudinal Disp. ΔY (in)	Vertical Disp. ΔZ (in)
1	Bracing attached No Panel attached	7	0	0.025	-0.0003
		10	0	0.025	-0.0003
2	No Bracing attached Panel attached	7	0	5.5919	-0.0003
		10	0	5.5919	-0.0003
3	Bracing attached Panel attached	7	0	0.025	-0.0003
		10	0	0.025	-0.0003

The result of interest here is, ofcourse, the longitudinal displacement, ΔY. As expected, the results show a huge difference between the deflection of a braced system and a non-braced one. However, the results also show that inherent roof system stiffness was modeled successfully since, otherwise, the analysis software would have detected an instability when the vertical braces were removed. The last thing these results show is that purlin end restraint does affect the outcome of the analysis, and longitudinal deformations are reduced when the purlin ends are restrained.

Perhaps the most telling outcome of this study can be seen in the graph shown in Figure 6. This graph shows the variation of longitudinal displacement of an unbraced model with a varying number of bays and purlin end conditions. As the figure shows, the longitudinal displacement of the eave is quite a bit larger for the one bay system than for the two bay system, and then it keeps decreasing exponentially as the number of bays increases.

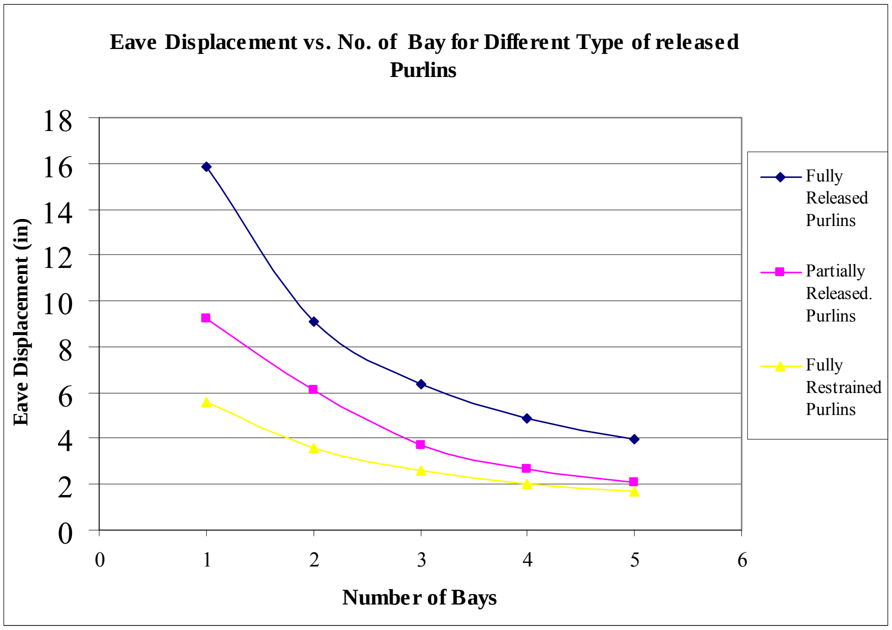

Figure 6: Longitudinal Building Displacement at Eave for a Varying Number of Bays and with Various Purlin End Restraint Conditions. (Figure 4.3 in Hamdallah 2005)

Furthermore, the decrease in longitudinal displacement seems to be more pronounced in systems where the purlins were not restrained, and the effect of purlin end restraint condition tends to diminish as the number of bays increases.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations of this research work may be summarized in the following:

Computer modeling of complete structural systems and their components is a methodological process that requires a thorough understanding of the system or component being modeled and an adequate knowledge of available modeling tools and techniques.

Modeling the interaction between primary and secondary structural components can be achieved and possibly produce a realistic assessment of the behavior of the whole structural system. This research showed that even small amounts of retraint can be modeled adequately. However, the results need to be validated through an experimental testing program.

Increasing the number of bays in an industrial steel building increases the structure's longitudinal stiffness exponentially. A drastic increase in stiffness can be observed when the number of bays is increased from one to five. The curve seems to tend to level-off, however, for a number of bays greater than five.

Longitudinal building deformation is more pronounced when purlins have no end-restraint. Moreover, purlin end restraint condition tends to affect the building's longitudinal stiffness with larger effects observed for a smaller number of bays.

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