Practical Approach to Designing Wood Roof Truss Assemblies

Rakesh Gupta, M.ASCE[1]; and Pranueng Limkatanyoo[2]

Abstract: The objective of this research was to use a three-dimensional (3D) analysis method to evaluate "system effects" in light-frame roof truss assemblies. The goal of this study was to develop an improved and practical design method for 3D roof truss assemblies used in residential construction. A truss plate manufacturer (TPM) design software was used to lay out assemblies and to design individual trusses. The TPM software used a conventional design procedure (CDP) by analyzing one truss at a time in two dimensions. A commercially available structural analysis program was utilized to model and analyze 3D truss assemblies as a system. This system design procedure (SDP) is being proposed as a tool to analyze and design 3D roof truss assemblies. Three truss assemblies, L shape, T shape, and a complex assembly, were analyzed. The structural responses including combined stress index (CSI), truss deflections, and reactions from both CDP and SDP were compared and the system effects were evaluated. From this investigation, it is concluded that there are three system effects observed by the SDP, but not accounted for by CDP. These are: reduced applied load effect, truss-to-truss support effect, and stiff truss effect. Based on this investigation, the maximum CSI for most trusses in all three assemblies reduced by 6–60% because of system effects. SDP can help to improve the design of truss assemblies by directly including system effects that are not accounted for by the CDP.

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Introduction

Roof trusses are one of the main structural components in residential and light-commercial structures. To construct a light-frame wood roof truss assembly, the trusses are erected and typically spaced 0.61 m on center. The sheathing is then nailed to the narrow face of the truss top chord members. Not only is the roof sheathing used to cover the facility and carry imposed loads, but it also serves as a load-distributing element among trusses in the assembly. This construction characteristic causes the truss assembly to act as a system. However, truss assemblies have been traditionally analyzed and designed on a single truss basis, i.e., two-dimensional (2D) analysis, which assumes that each truss in the assembly carries loads based on its tributary area. To account for system effects in the assembly, a 15% increase in allowable bending stress, and 10% increase in allowable tensile and compressive stresses are currently allowed in members used in the roof assembly (ANSI 2002). This overall approach is known as the conventional design procedure (CDP). The CDP is relatively simple, and is assumed to be conservative. However, the CDP does not take into account all the "system effects" encountered in realistic assemblies, which may or may not be conservative in actual assembly behavior. Therefore, our research hypothesis was "There are system effects that are present in a 3D truss assembly that are not accounted for by current design procedures, and that could be directly included by analyzing a 3D frame model of the assembly."

In this paper, the research hypothesis will be evaluated by using a system design procedure (SDP) to include the system effects directly in the design of light-frame roof truss assemblies by using three-dimensional (3D) analysis. SDP has the potential to improve the efficient use of wood as a raw material. It will also provide a better understanding of the structural behavior of wood roof truss assemblies by integrating truss design into the whole building design process which is the future of the home building industry (NAHB 2001; Meeks 1999, 2000).

The main objectives of this study were as follows:

1. To develop a practical, 3D assembly model composed of relatively simple 2D truss analogs, to represent 3D, light-frame wood roof truss assemblies; and
2. To verify that by using the 3D assembly model, system effects that are not accounted for by the conventional design method can be directly included.

The rationale for this study is to develop an improved and practical method to determine the structural performance of 3D roof truss assemblies used in residential construction. This proposed research hopes to improve the understanding of roof truss assembly behavior, determine the sources of the most significant system effects, and develop methods useful in analyzing and designing complex roof assemblies for residential buildings.

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Literature Review

Several researchers (Cramer and Wolfe 1989; Rosowsky and Ellingwood 1991; Li et al. 1998; Gupta et al. 2004; Cramer et al. 2000) have developed computer analysis methodologies to include system effects. There are two primary approaches to include the system effects in a roof truss assembly. The first method (Cramer and Wolfe 1989; Rosowsky and Ellingwood 1991; Cramer et al. 2000) is to determine a "system factor" for a type of assembly. This approach is used in the CDP for truss structures that qualify as repetitive-member structures. However, based on the *National Design Specification for Wood Construction* (AF&PA 2005), a system factor (repetitive-member factor) is only applied to modify the allowable bending stress. Recently, ANSI (2002) has recommended a repetitive-member factor for allowable tensile and compressive stresses. In the second approach, system effects are examined directly by analyzing the entire 3D roof truss assembly. The second approach is relatively new and has been studied by Li et al. (1998) and Gupta et al. (2004). This is an alternate approach to investigate the system behavior of light-frame wood truss assemblies and their studies will be used as a foundation and starting point in this investigation.

A detailed literature review on all aspects of wood roof truss assemblies is given in Limkatanyoo (2003).

Research Methodology

To evaluate the system effects in 3D truss assemblies a truss plate manufacturer (TPM) software was used as CDP and a commercial, general-purpose structural analysis software (SAP2000) was used as SDP. TPM software, used by commercial truss fabricators, was used to lay out assemblies and to design individual trusses. The program lays out 3D truss assembly and performs 2D truss analysis, providing structural responses in terms of member forces, deflections at panel points, reactions, and combined stress index (CSI) values. SAP2000, a commercially available, integrated software program for structural analysis and design, which is extensively used by practicing engineers, was used in this study to analyze 3D assemblies. SAP2000 was used as a tool, and any software capable of 3D analysis can be used for 3D analysis and design of assemblies. The structural outputs from this program are member forces, deflections at joints, and reactions. CSI values were generated using a spreadsheet in order to compare CSI values from individual trusses.

The research methodology included: (1) modeling 2D truss (in TPM software and SAP2000) and 3D truss assemblies (in SAP2000); and (2) evaluating system effects by analyzing 3D truss assembly models.

2D Truss Modeling—Joint Connectivity

This study intends to offer a simple and practical way to model joint connectivity by considering all the joints in the truss either as pinned or rigid. This is convenient and simpler than one including semirigid connections. The heel joints are assumed as rigid connections in this study. The top and bottom chord members are continuous at the panel points. The webs are pin connected to the chords. The ridge joint is also assumed to have a pinned connection. These assumptions are used in design practice and are recommended by TPI-2002. Although the connections actually have nonlinear behavior, this study will be focused on the service load range, so only linear behavior of the metal plate connectors will be considered. This approach offers tremendous advantages by reducing the level of complexity in modeling three-dimensional truss assemblies, including component interactions that may occur, and yet providing acceptably accurate structural behavior. Moreover, the results of truss analysis using pin and rigid connection is very close to truss analysis with partial fixity of the joints, as shown in this study (Limkatanyoo 2003). Additionally, as shown later in this paper, 3D system effects have a much greater influence on truss behavior (and system behavior) than fixity of joints.

Additional details of 2D truss modeling are given in Limkatanyoo (2003).

Modeling Three-Dimensional Truss Assembly

After the 2D truss design analogs were modeled, the individual trusses were connected to represent the actual 3D roof assembly. Modeling a 3D roof truss assembly included adding specialty: (1) load-distributing elements; and (2) boundary conditions.

Load-Distributing Elements

Frame elements were employed to simulate the roof sheathing as a load-distributing element in SAP2000. However, a plate element, which is more suitable to represent a flat surface, may be more appropriate and may be used in a future research study. A frame element was used here to keep the model simple and practical.

Roof sheathing has two primary structural effects: two-way action and partial composite action (T-beam action). Partial composite action improves the performance of structures by increasing the stiffness and strength (McCutcheon 1977). However, truss top chord members have much higher flexural stiffness than the sheathing. Thus, the strength and stiffness of the overall truss system are only slightly increased by considering partial composite action in the design (Liu and Bulleit 1995). Moreover, a parametric study (Limkatanyoo 2003) showed that the T-beam action only increases the stiffness by an average of less than 5% compared with the truss top chord members' stiffness alone. Therefore, to meet the goal of a relatively simple assembly model, partial composite action was not included in this study.

Roof sheathing forms a wide and thin beam in the direction perpendicular to the trusses. The roof sheathing slightly increases the stiffness of the top chord members and also significantly distributes loads and reduces differential deflections among the trusses in the assembly. This effect of roof sheathing is known as "two-way action." Several research studies (Cramer and Wolfe 1989; Cramer et al. 2000; LaFave and Itani 1992; and Gupta et al. 2004) included the two-way action effect using sheathing beam elements to represent roof sheathing connected on top of the truss top chord members. In Cramer and Wolfe (1989), the sheathing beams were rigidly connected to truss top chord members. Although the two-way action of roof sheathing plays a significant role in the system behavior of truss assemblies, there are no standardized methods for its modeling. We are modeling two-way action of sheathing beams based on engineering judgment.

Sheathing beams were modeled using frame elements with a row of these elements representing a row of roof sheathing. Each row of roof sheathing elements represents a tributary width of actual sheathing width (1.22 m). The sheathing beam element was assigned the same thickness, width, and modulus of elasticity (MOE) as the actual sheathing panel. Sheathing properties were obtained from the APA—The Engineered Wood Association

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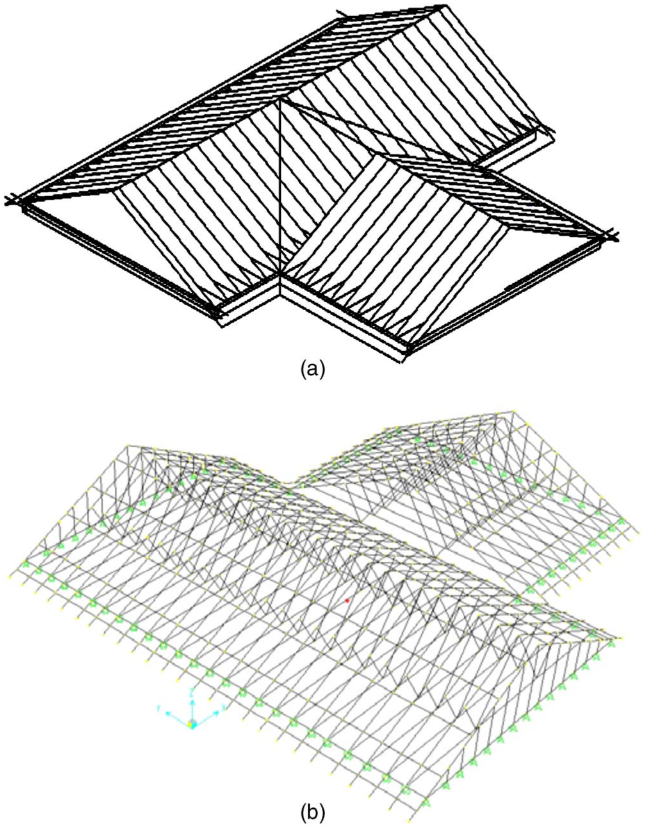

Fig. 1. T-shaped assembly: (a) TPM layout; (b) SAP2000 model

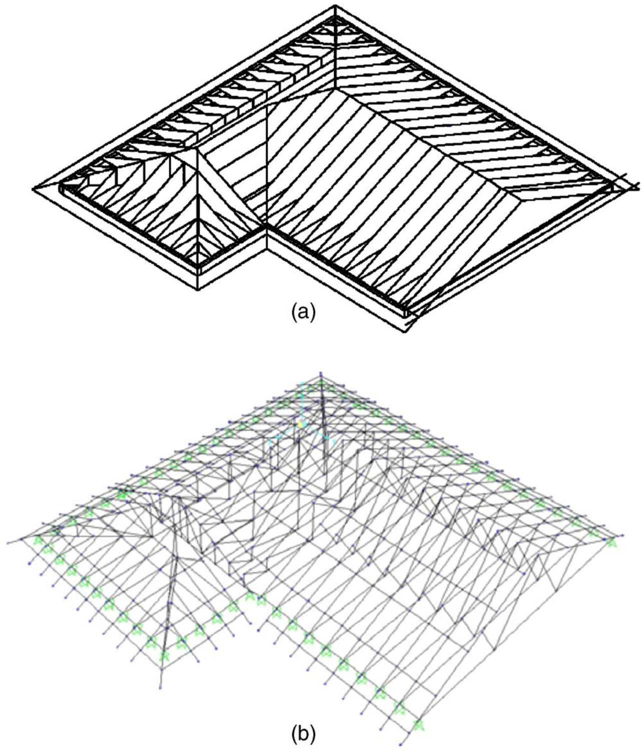

Fig. 2. L-shaped assembly: (a) TPM layout; (b) SAP2000 model

(1997). As in the actual situation, the major axis of a sheathing beam element was perpendicular to the truss top chord slope and the minor axis is parallel with the truss top chord. Most research studies with modeling of load-distributing elements have assumed discontinuities in the model at the same locations as the actual discontinuities between sheathing panels. This discontinuity assumption may not provide the best modeling of the load-distributing elements because more nails are used at the locations where the sheathing panels meet, thus possibly making them even stiffer than other locations. Hence, in this study, the sheathing beams were rigidly connected to the truss top chord with no discontinuities between sheathing panels.

Boundary Conditions

Actual roof truss assemblies are supported by walls and connected to the top plate of the wall. Overall structural behavior of the roof system depends not only on the trusses, but also on the support conditions and wall properties. Since only the roof truss assemblies will be modeled, without fully representing the walls, an appropriate modeling approach to simulate the boundary conditions is needed.

In the CDP, trusses are designed and analyzed for support conditions with pin support on one end and roller support on the other end. This assumption is not realistic because trusses are almost always connected with a framing connector to the wall top plate the same way on both ends of the trusses. Therefore, the conventional assumption may not be suitable for analyzing the actual light-frame wood truss assembly in 3D.

Gupta et al. (2004) used pinned supports on both ends of the trusses in their roof assembly model. This symmetrical approach may be simpler than arbitrarily assigning a pinned support at one end and a roller support at the other. However, in real buildings, the horizontal movement of the truss bottom chord is not completely prevented. Thus, assuming all the supports in the roof assembly as pinned may not be the best approach. As noted by Gupta et al. (2004), the support conditions significantly affect the structural performance of light-frame wood truss assemblies. To accurately predict the structural behavior of light-frame wood truss assemblies, a more suitable boundary condition must be developed for the proposed assembly model.

In addition to the properties of the supporting walls, the locations of cross and end walls also determine the support conditions (in the plane of the trusses). In other words, the cross and end walls help to resist the out-of-plane deformation of the supporting side walls, and thus resist movements at the support in the plane of the truss. It may be reasonable to treat all the truss supports located at intersections between end or cross walls and side walls as pinned, to resist translation. For trusses on side walls located elsewhere, much smaller lateral resistance will be provided, and can perhaps be ignored. Diaz and Schiff (1998) proposed similar boundary conditions for assemblies composed of similar trusses with good results. Therefore, based on their preliminary findings, truss supports will be assumed as pinned where the side walls and end or cross walls intersect. Roller supports are assumed where side walls do not meet with either cross or end walls. This assumption provides a more realistic simulation than Gupta et al. (2004) where the boundary conditions were all assumed to be pinned supports. Yet, it provides simplicity and practicality to model 3D truss assemblies. Finally, the wall top plate will be modeled using frame elements with the same physical properties as the actual top plate, and be rigidly connected to the heel joints.

Three-Dimensional Truss Assembly Models

The TPM software was used to lay out entire T-shaped, L-shaped, and complex truss assemblies as shown in Figs. 1(a), 2(a), and

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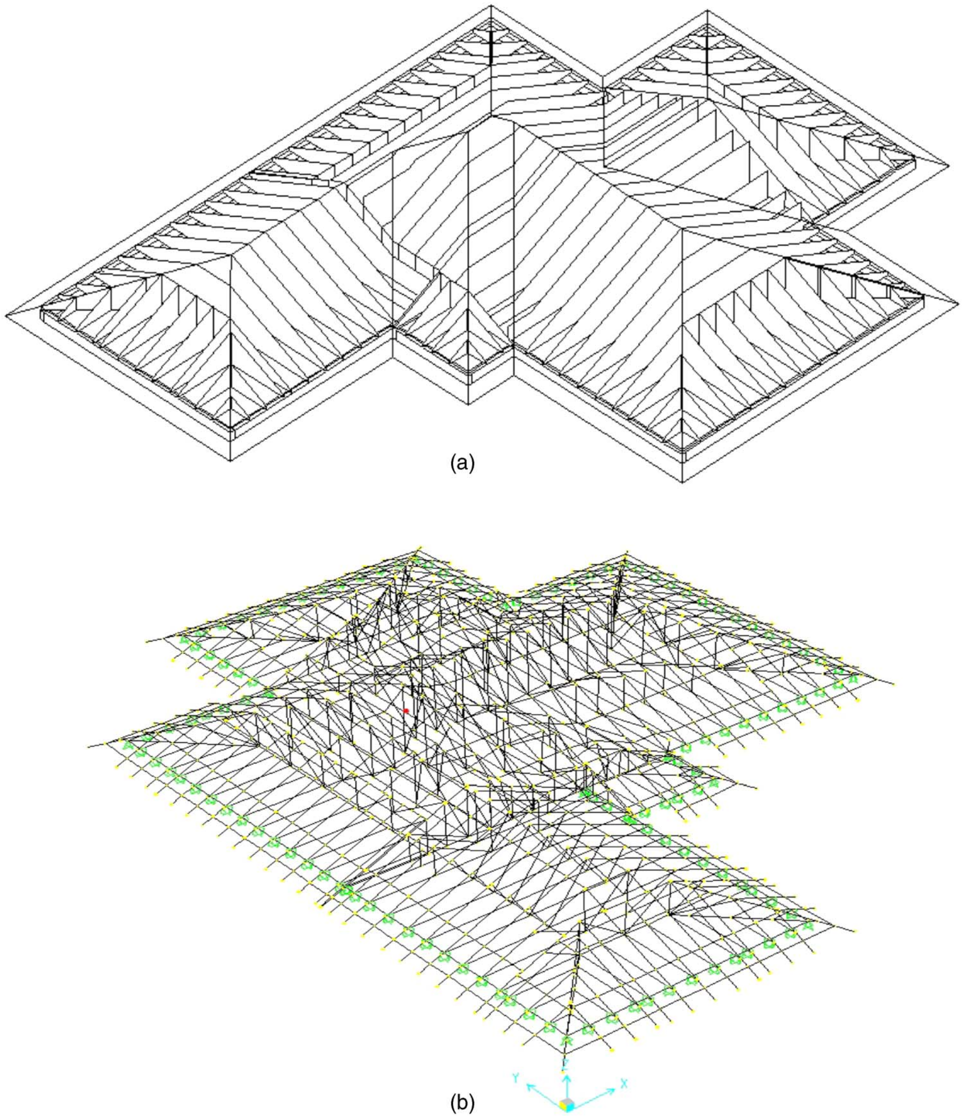

Fig. 3. L-shaped assembly: (a) TPM layout; (b) SAP2000 model

3(a), respectively. TPM software provides geometry, loading conditions, material properties, and analyzes each truss individually. All the input parameters for T-shaped, L-shaped, and complex truss assemblies are given in Limkatanyoo (2003).

Based on the geometry, material properties, and loading obtained from TPM software, 3D frame models of the T-shaped, L-shaped, and complex assemblies were generated for analysis in SAP2000. These models are shown in Figs. 1(b), 2(b), and 3(b). Results from SAP2000 and TPM will be compared in terms of maximum CSI values for each truss and their locations, deflections, and truss reactions. If the results do not match, then our research hypothesis is true and there are system effects that are not fully accounted for by conventional truss design. These system effects will be described, and may include the support conditions (trusses supported by other trusses for example), presence of stiff gable end trusses, and others that may be identified.

For additional details on all aspects of modeling, see Limkatanyoo (2003).

Results and Discussion

Verification of 2D Truss Models

Two-dimensional truss models of all individual trusses from three assemblies were verified by analyzing them in SAP2000 and comparing the results (CSI and deflections) against results obtained from TPM software. The verification results showed that our design analog can be used to represent actual trusses. Details of the verification are given in Limkatanyoo (2003).

Three-Dimensional Assembly Model Check

The results from assembly analysis were first checked against the expected structural behavior (response) and basic statistics. The structural response check includes a deflection check and support reaction check. The deflection check of the T-shaped assembly showed the expected structural response in terms of deflection, i.e., all trusses displacing outward at supports except at

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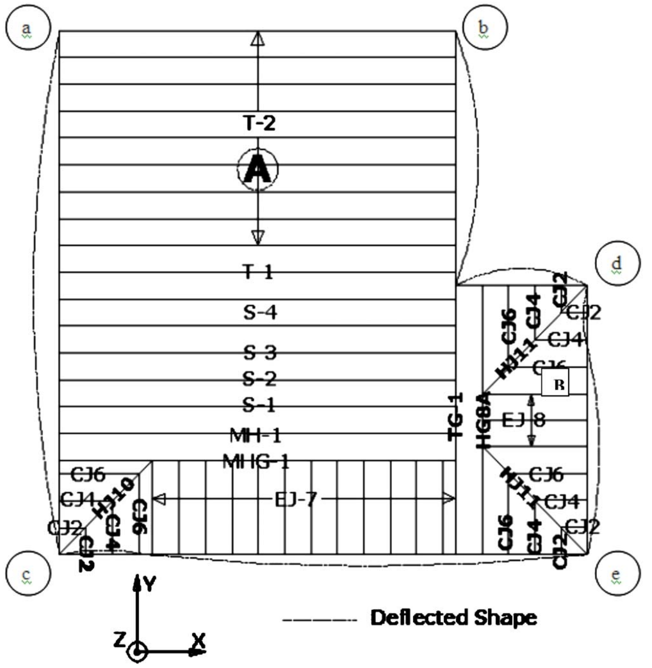

Fig. 4. Horizontal deformation of supports for trusses in L-shaped assembly

corners where deflection is negligible due to stiff gable end trusses. However, the L-shaped assembly (Fig. 4) deflects differently from the T-shaped assembly, especially at corners with hip jack trusses. At corners c and d of the L-shaped assembly, one side of the boundary moves outward while the other side of the boundary moves inward as shown in Fig. 4. Corner e had a different response than corners c and d, probably due to interaction between the two hip assemblies (HJ11 and HJ12) in subassembly *B*. Additionally, deflections were verified for the complex assembly and the results matched the expected structural response very well.

After the loads are applied to the structure, they are transferred to the supports. Therefore, the applied loads must equal the sum of the reactions. The support reactions for all three assemblies match the applied loads very well. For details, see Limkatanyoo (2003).

System Effects

Reduced Applied Load

In the CDP, it is assumed that each truss is loaded based on its tributary area and trusses are assumed to be spaced 0.61 m on center (o.c.) with a tributary width of 0.61 m. The CDP assumes that all the trusses in an assembly have the same tributary width. Although this assumption is applied to all trusses, in a real situation, some trusses may be spaced more or less than 0.61 m. The SDP considers the actual geometry of the assembly and assumes that each truss carries loads based on the actual tributary area and geometry of the assembly. Therefore, the tributary width may be more or less than 0.61 m.

This effect is recognized in all three assemblies in this study. In most assemblies, some trusses frame into other trusses and carry loads from those trusses. This effect is not considered by the CDP. However, the SDP accounts for this effect. Therefore,

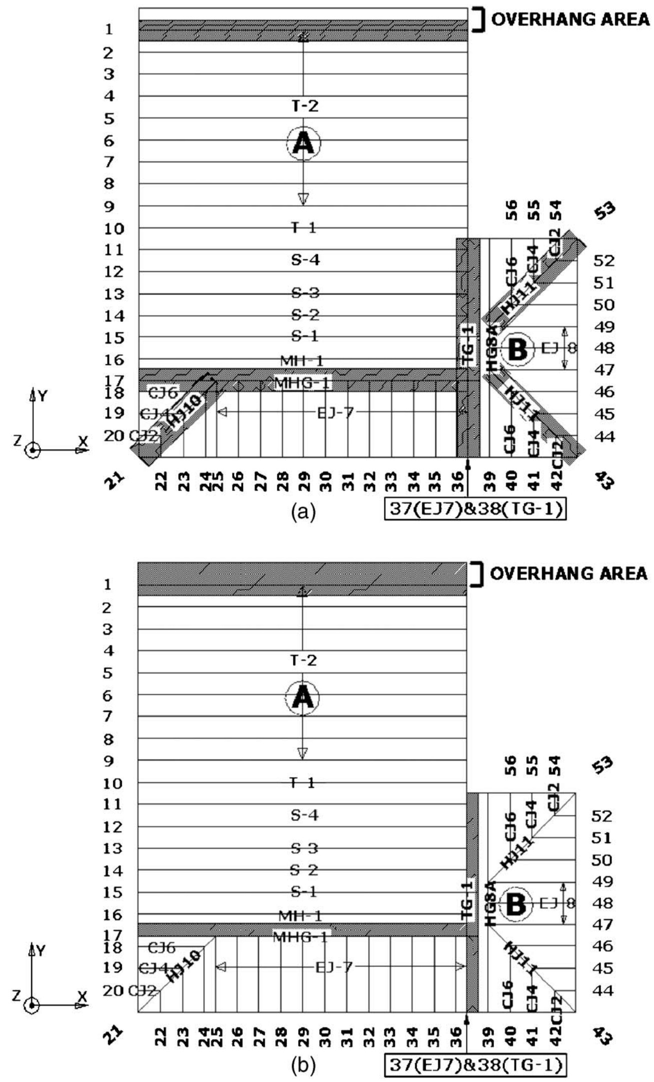

Fig. 5. Tributary areas of T-2, MHG-1, TG-1, HJ-10, and HJ-11 trusses in L-shaped assembly assumed by: (a) CDP; (b) SDP

trusses analyzed by the SDP have the actual tributary loading area, which is usually smaller than assumed by the CDP.

This system effect is discussed below for the L-shape assembly analyzed in this study and results for the two other assemblies are give in Limkatanyoo (2003):

1. Figs. 5(a and b) show the tributary areas of the T-2 truss located on the edge of the roof based on the CDP and SDP, respectively. The L-shaped assembly happens to have 0.61-m overhangs and no gable end trusses, so the actual tributary width of this T-2 truss at Location 1 is 0.91 m (0.3 m on the inner side and 0.61 m of overhang). The CDP does not account for the overhang of the truss on the edge of the assembly and assumes a tributary width of 0.61 m. However, the SDP considers the overhanging roof and has a tributary width of 3 ft. Table 1 shows the CSI values for the T-2 truss (Fig. 6) at Location 1 obtained using the CDP and SDP, and their percent differences. For all of the truss members, the CSI increases range from 10 to 33%. The CSI increases by 10% for Member 2 and by 17% for Member 3. In both cases, the CSI analyzed by the SDP is more than 1.00, which is the upper limit in design. It shows that the T-2 truss is unsafe based on the SDP, but the T-2 truss is safe based on the CDP.

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Table 1. CSI Comparison for T-2 Truss from L-Shaped Assembly Analyzed by TPM (CDP) and SAP2000 (SDP)

Member number	CSI values TPM (CDP)	CSI values SAP2000 (SDP)	Percent increase (+)/ decrease (−) (%)
0	0.277	0.339	22
1	0.768	0.932	21
2	0.971	1.072	10
3	0.971	1.135	17
4	0.768	0.94	22
5	0.277	0.341	23
6	0.704	0.811	15
7	0.565	0.683	21
8	0.704	0.852	21
9	0.252	0.336	33
10	0.339	0.415	22
11	0.339	0.438	29
12	0.252	0.291	15

Table 2. CSI Comparison for TG-1 Truss from L-Shaped Assembly Analyzed by TPM (CDP) and SAP2000 (SDP)

Member number	CSI values TPM (CDP)	CSI values SAP2000 (SDP)	Percent increase (+)/ decrease (−) (%)
1	0.838	0.402	−52
2	0.724	0.491	−32
3	0.843	0.277	−67
4	0.709	0.310	−56
5	0.972	0.687	−29
6	0.822	0.397	−52
7	0.600	0.340	−43
8	0.778	0.678	−13
9	0.905	0.382	−58
10	0.946	0.517	−45
11	0.870	0.524	−40

This shows that a system effect, not accounted for by CDP but included in the SDP, can cause the structure to be unsafe. It shows an advantage of the SDP by predicting more accurate structural responses by directly including system effects. The maximum percent increase in CSI occurred in truss member 9 where the CSI increased by 33%. Although the applied load in the SDP is about 50% higher than from the CDP, the CSI only increases by 33%. This is because the T-2 truss in the assembly is connected with other trusses by load-distributing elements, and the load is transferred through the load-distributing elements to adjacent trusses. This phenomenon is also supported by the results of Wolfe and McCarthy (1989) and LaFave and Itani (1992), where a loaded truss only carries 60–80% of the load applied to it;

2. The T-2 truss is a symmetrical truss. Based on the CDP, the CSI values for both sides of the symmetrical truss are equal. However, this is not always the case for the truss analyzed by the SDP. In an assembly, load-distributing elements which connect and align perpendicular to the truss top chord transfer load among trusses. In Table 1, CSI values on both sides from the CDP are equal. However, based on the SDP, CSI values of members (2 and 3) on both sides are not equal, because load-distributing elements transfer load differently depending on their position with respect to the overall shape of the assembly. The load-distributing elements on truss Member 3 transfer axial load of 111 N while the load-distributing elements on truss Member 2 transfer axial load of 67 N. This shows that with more load transferred through the load-distributing element on one side, the CSI of truss Member 2 is 1.072 and the CSI of truss Member 3 is 1.135. Because the difference in load transferred through the load-distributing elements is only 45 N, the difference in CSI is also small (0.053 difference in CSI). It shows that the position of load-distributing elements with respect to the overall shape of the assembly also affects how load is distributed among trusses in an assembly. It is recommended that a future study investigate the effect of load-distributing elements. Additionally, other T-2 trusses based on the SDP show the same trend for CSI, that all members of the T-2 truss based on the SDP have higher CSI values than those obtained from the CDP;
3. Several trusses (S-1, S-2, S-3, S-4, MH-1, and MHG-1) frame into the TG-1 truss as shown in Figs. 5(a and b). Additionally, one of the EJ-7 trusses at Location 37 is right next to TG-1. Therefore, based on the SDP, TG-1 had a tributary width of only 0.3 m (from right side only) for this configuration. The tributary areas of the TG-1 truss analyzed using the CDP and SDP are shown in Figs. 5(a and b), respectively. Therefore, by using the SDP, the load decreases about 50% when compared with that assumed by the CDP. Table 2 provides the CSI values for the TG-1 truss obtained from the CDP and SDP and their percent differences. Fig. 7 shows the TG-1 truss. For all of the members of the TG-1 truss, when using the SDP, the CSI goes down from 13 to 67%. CSI values of this truss (TG-1) analyzed by the SDP are lower than those analyzed individually (CDP). The maximum CSI of the TG-1 truss decreases from 0.972 (CDP) to 0.687 (SDP). Although the applied load goes down by 50%, the maximum CSI only decreases by 29%. This is because the two-ply girder TG-1 truss is stiffer than its adjacent trusses. Hence TG-1 attracts more load, resulting in a higher CSI than expected (50%) reduction in CSI. In addition

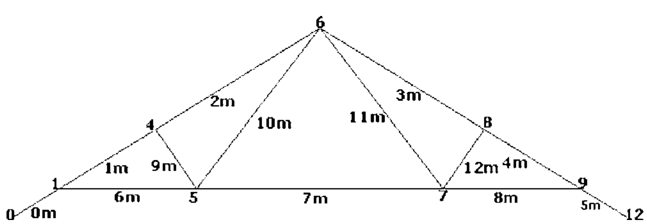

Fig. 6. Individual T-2 truss in L-shaped assembly

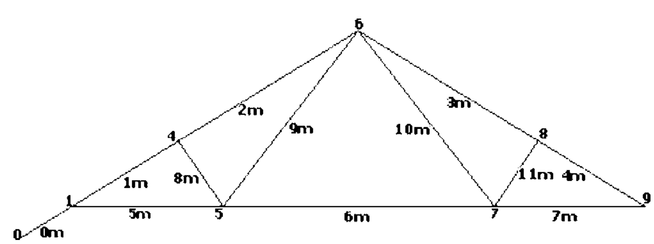

Fig. 7. TG-1 truss in L-shaped assembly

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Table 3. CSI Comparison for HJ-10 Truss from L-Shaped Assembly Analyzed by TPM (CDP) and SAP2000 (SDP)

Member number	CSI values TPM (CDP)	CSI values SAP2000 (SDP)	Percent increase (+)/ decrease (−) (%)
0	0.624	0.113	−82
1	0.474	0.207	−56
2	0.857	0.272	−68
3	0.001	N/A	N/A
4	0.970	0.364	−62
5	0.196	N/A	N/A
6	0.435	0.043	−90
7	0.107	0.074	−31

to the TG-1 truss, the same also occurs in the MHG-1 truss (at Location 17) and the same result also applies to the MHG-1 truss. The tributary areas of the MHG-1 truss analyzed by the CDP and SDP are also shown in Figs. 5(a and b), respectively; and

4. In subassembly *A*, the hip jack truss (HJ-10) is connected to the corner jack trusses (CJ2, CJ4, and CJ6) and the girder truss (MHG-1 truss). Figs. 5(a and b) show the tributary areas of the HJ-10 truss analyzed using the CDP and SDP, respectively. The connecting (CJ-2, CJ-4, and CJ-6) trusses carry the load for the HJ-10 truss. Hence, by using the SDP, there is no load applied to the HJ-10 truss. Table 3 shows the CSI values of the HJ-10 truss in the L-shaped assembly obtained from the CDP and SDP and their percent differences. Fig. 8 shows the individual HJ-10 truss. For all of the members of the HJ-10 truss, when the truss is analyzed using the SDP, the CSI goes down from 31 to 90%. CSI values of this truss (HJ-10) analyzed by the SDP are lower than those analyzed using the CDP. The maximum CSI of the HJ-10 truss decreases from 0.970 (CDP) to 0.364 (SDP) by 62%. The maximum percent decrease in CSI occurs in truss Member 6, which is about 90%. The HJ-10 truss is connected to CJ trusses (i.e. CJ-2, CJ-4, and CJ-6 trusses). When the assembly is analyzed by the SDP, the load is transferred from the CJ trusses to the HJ-10 truss through the load-distributing elements. Although the HJ-10 does not carry applied load directly, the load transferred from the CJ trusses is properly accounted for, when analyzed by the SDP.

Deflection Compatibility

Currently, the CDP assumes that a truss has a roller support on one end and a pin support on the other end. Both types of supports have vertical restraint, which do not allow for any vertical deflection. In reality, trusses are not always supported by a wall, but sometimes supported by other trusses. Therefore, the vertical deflection at the end that is supported by other trusses is not zero.

The CDP analyzes one truss at a time and assumes zero vertical deflection at both supports for all trusses in an assembly. When the CDP analyzes the supporting truss, there is a vertical deformation at the connecting point. Therefore, at the same (connecting) point in the assembly there are two different deflection values predicted by the CDP. This shows that the CDP provides displacement incompatibility, which represents unrealistic results. For example, based on the CDP, the T-2 truss in the T-shaped assembly (Fig. 9) has zero displacement at the connecting point,

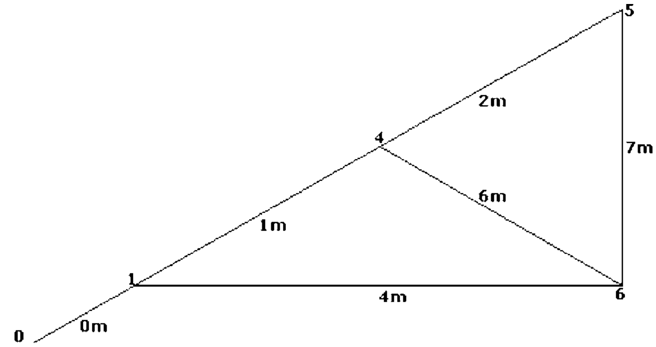

Fig. 8. HJ-10 truss in L-shaped assembly

where the T-2 truss is supported by the TG-1 truss. However, analysis (CDP) of the TG-1 truss shows that the connecting point has a deflection of 0.6 mm.

Unlike the CDP, the SDP simultaneously analyzes all the trusses in an entire assembly. Therefore, it provides the same deflection for all the connecting points between trusses supported by other trusses. This shows that the SDP gives displacement compatibility, which represents realistic results. Detailed results for all three assemblies are given in Limkatanyoo (2003).

This system effect is called the truss-to-truss support effect. The current design method does not recognize the truss-to-truss support effect because it assumes the same support conditions (pinned-roller supports) for all trusses in an assembly, even though some trusses may not have the same support condition, as mentioned earlier. This may lead to excessive deflection differences at the connecting points between trusses.

Stiffer Truss

It is a well known fact that in an assembly stiffer trusses generally attract more load and affect how load is distributed among trusses in the assembly. In this investigation, the stiffer trusses in the assembly are gable-end trusses, two-ply girder trusses, and the trusses in hip systems. Because these stiffer trusses attract more load, the adjacent trusses attract less load, resulting in lower member forces, and lower CSI values in adjacent trusses.

All assemblies have stiffer trusses which attract more load, and here it is shown using L-shaped assembly. The gable-end trusses are not present in the L-shaped assembly, but there are two-ply girder trusses in this assembly. This two-ply truss is stiffer than regular trusses because it is composed of two trusses nailed/stapled together. The stiffer truss attracts more loads. The combined reactions of the two-ply girder S-1 truss based on the CDP are 1.6 kN while the combined reactions of the S-1 truss based on the SDP are 1.7 kN. In the SDP, the reactions are higher than those analyzed by the CDP because the S-1 truss is a stiffer truss compared to adjacent trusses and attracts more load.

Table 4 shows the CSI values of selected members of the S-1 truss from the L-shaped assembly analyzed by the CDP and SDP and their percent differences. Only truss members with high CSI differences are selected including one overhang, four top chord members, two bottom chord members, and four web members. The S-1 truss is shown in Fig. 10. For all of the truss members of the S-1 truss, when analyzed based on the SDP, the CSI increases by 11–88%. This is because the S-1 truss is stiffer and attracts more loads. The maximum CSI in this truss occurred in top chord Member 6, which increased from 0.891 (CDP) to 0.988 (SDP), i.e., by 11%. Both analysis methods (CDP and SDP) show the same member receiving the maximum CSI values. The average

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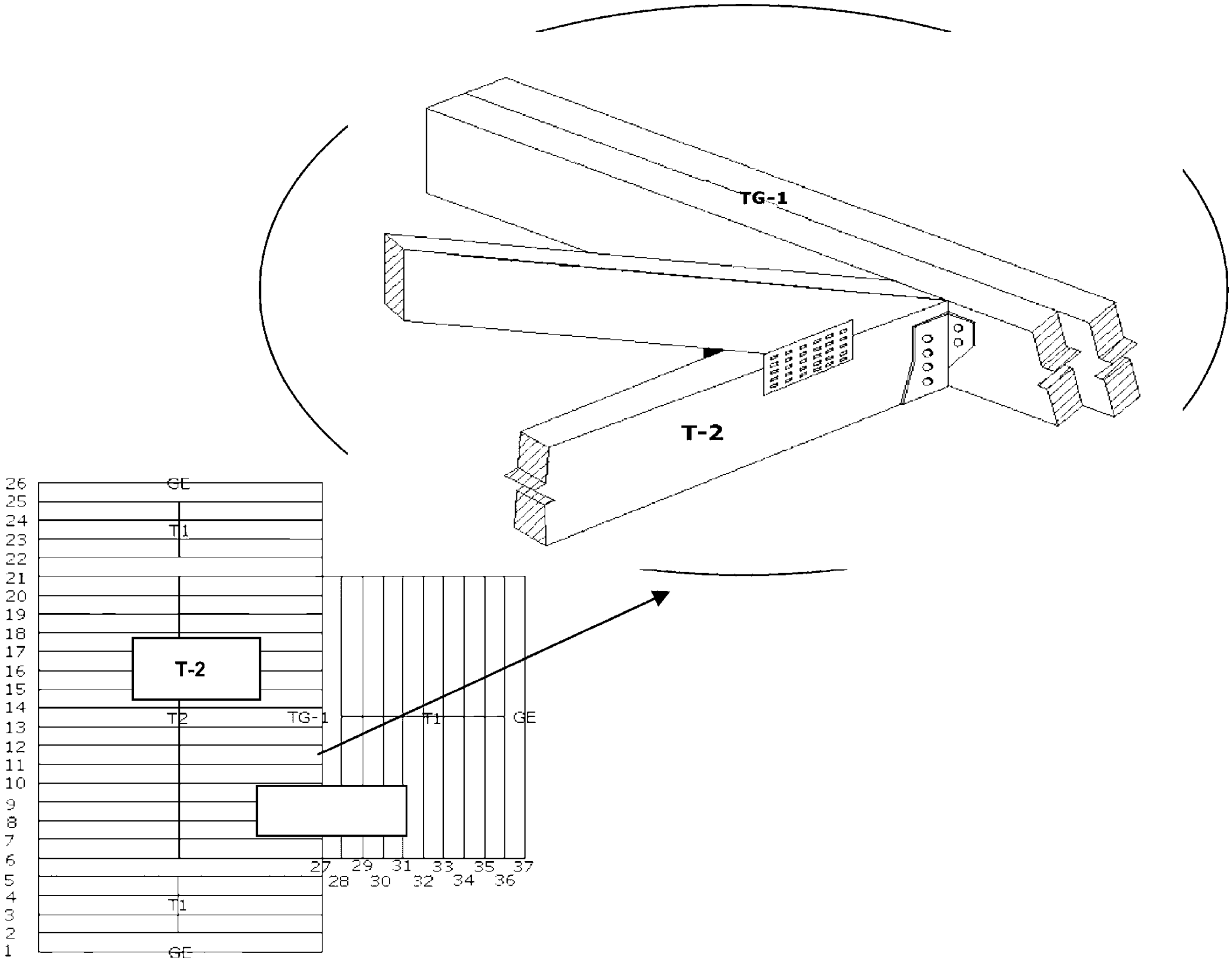

Fig. 9. Connecting point between T-2 truss at Location 14 and TG-1 truss in T-shaped assembly

percent increase is only 51% even though the S-1 truss is two S-1 trusses nailed together. This is because although the truss is a two-ply truss, its stiffness is not two times the stiffness of one truss. Moreover, a truss in an assembly with load-distributing elements does not carry its entire applied load, but the load is transferred to adjacent trusses through the load-distributing elements.

In addition to the stiffer two-ply truss, the hip system is also stiffer than adjacent trusses. The hip system in the L-shaped assembly is composed of Corner Jack trusses and Hip Jack trusses. Because the hip system contains a group of trusses with shorter spans (0.61–1.83 mm) when compared with the Fink trusses (6.1–8.5 m span), it is stiffer than the adjacent trusses. Moreover, based on their reaction to comparison results, the combined reactions of hip system trusses are higher when analyzed based on the SDP. This shows that CJ [Subassembly *B* in Figs. 5(a and b)] trusses attract more load. As a result, the maximum CSI of Corner Jack trusses, CJ-2, CJ-4, and CJ-6, increases by 45, 79, and 13%, respectively, as shown in Table 5. The CSI increase in CJ-6 is not as high as those in CJ-2 and CJ-4 trusses. This is because CJ-2 trusses, which are located next to the overhang, have a tributary area from the roof overhang. Based on the SDP, CJ-2 trusses have a higher tributary width of 0.91 m, while the CDP only assumes a 0.61-m tributary width for all trusses. Therefore, the CSI increase for the CJ-6 truss based on the SDP is not as high as other corner jack trusses.

In addition to all the system effects mentioned earlier, the modeling method also affects the structural response. In this investigation, it shows that the location of load-distributing elements also affects how load is transferred among trusses in the assembly. For example, the top chord member of the EJ-7 truss at

Table 4. CSI Comparison for S-1 Truss from L-Shaped Assembly Analyzed by TPM (CDP) and SAP2000 (SDP)

Member number	CSI values		Percent increase (+)/ decrease (−) (%)
	TPM (CDP)	SAP2000 (SDP)	
0	0.185	0.262	42
2	0.245	0.419	71
4	0.176	0.262	49
5	0.061	0.09	48
6	0.891	0.988	11
8	0.313	0.484	55
10	0.237	0.369	56
12	0.089	0.132	48
13	0.083	0.15	81
16	0.05	0.094	88
19	0.26	0.45	73

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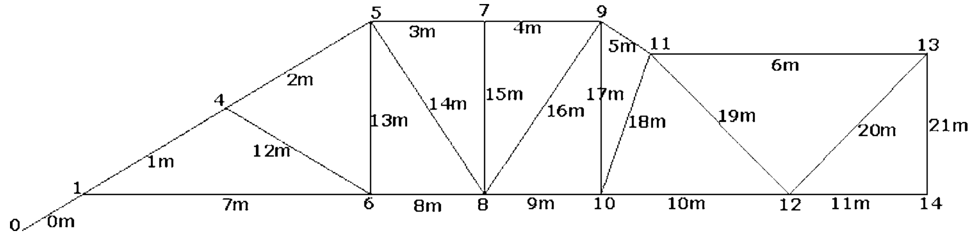

Fig. 10. S-1 truss from L-shaped assembly

location 32 (Fig. 5) is connected to the load-distributing element, which transfers loads among trusses in Subassembly A. Hence, the CSI of the EJ-7 truss at this location increases from 0.697 (CDP) to 0.864 (SDP) by 24% as shown in Table 5.

CSI Reduction

Because of the "system effects" discussed earlier, the CSI obtained from the SDP normally decreases when compared with those from the CDP. The reduction of CSI for each assembly is discussed below.

Table 6 shows a CSI summary for trusses in the T-shaped assembly analyzed by the CDP and SDP. The T-shaped assembly has three gable-end (GE) trusses. The GE trusses are stiffer and attract more load than adjacent trusses. The adjacent trusses, which are located next to the gable-end truss, attract less load, resulting in lower CSI. T-1 trusses at Locations 2, 25, and 36 in the T-shaped assembly (Fig. 9) are located next to the gable end truss. Although the adjacent trusses are affected by the stiffer truss (i.e., gable-end trusses), trusses located farther away from the stiffer truss are less affected. The T-1 truss at Location 37 is located farther away from the gable-end truss. Its CSI values decrease from 0.971 (CDP) to 0.905 by 7%. This shows that a truss (i.e., T-1 truss) located farther away from a stiffer truss (i.e., gable-end truss) has only a slight decrease in CSI.

For the T-2 truss, which is not located near the gable-end trusses in this assembly, the percent difference in CSI only ranges from −6 to +2%. This shows that gable-end trusses do not affect how load is distributed among the T-2 trusses. Another observation is made for the TG-1 truss. Its CSI decreases from 0.941 (CDP) to 0.847 (SDP) by 10%. This is because the TG-1 truss in the T-shaped assembly is framed by other trusses (T-2) and the SDP assumes that the connecting trusses (T-2) carry the load from the side where they connect. Only the load from one side of the truss is applied to it and the tributary width is about 1 ft. Therefore, by using the SDP, the load from the tributary area decreases roughly 50% when compared with that assumed by the CDP.

In summary, for the T-shaped assembly, maximum CSI values for most trusses decrease by 6–60% but CSI for one T-2 truss increases. This increase is only 2% in this assembly and the CSI is still below 1.00 but in some other assembly, even a 2% increase may bring the CSI over 1.00. This is exactly the condition not recognized by the CDP. Hence, the SDP provides improved safety of truss assemblies through advanced analysis.

Table 7 shows the maximum CSI of trusses in the L-shaped assembly (Fig. 5) analyzed by the CDP and SDP, and their percent differences. Their differences and reasons are discussed below.

1. The girder trusses, which are supported by other trusses, have smaller tributary areas as explained earlier. As a result, the girder trusses have a lower amount of applied load based on the SDP compared with those based on the CDP. Therefore, the CSI values of girder trusses (HG8A, MHG-1, and TG-1) in the assembly are lower than those based on the CDP;
2. The L-shaped assembly includes the hip system where trusses are framed into girder trusses, which leads to smaller tributary areas for some trusses. The HJ-10 truss in the hip system has no load due to its tributary area. This is because the Corner Jack trusses carry the load for the Hip Jack truss as aforementioned. Therefore, maximum CSI of all the hip jack trusses decreases;
3. Not only does the SDP assume smaller total applied load as in reality, but some trusses may have higher applied load based on the SDP. In the L-shaped assembly, the T-2 truss at Location 1 is connected to the overhang of the roof and it is assumed by the SDP to have a tributary area including the roof overhang. However, the CDP does not account for this effect. From Table 7, the CSI of the T-2 truss at Location 1 increased from 0.971 (CDP) to 1.135 (SDP). The CDP classifies the T-2 truss at Location 1 as safe, while the SDP shows that the truss does not pass the design criterion of CSI ≤ 1.00. This shows that the CDP does not account for the fact that there is a roof overhang connecting to the truss on the edge of the roof;
4. As explained earlier, trusses located next to stiffer trusses have lower CSI values when they are analyzed by the SDP.

Table 5. CSI Comparison for CJ and EJ Trusses from L-Shaped Assembly Analyzed by TPM (CDP) and SAP2000 (SDP)

Truss type	Max. CSI (TPM) (B)	Max. CSI (SAP) (C)	Percent increase $(C-B)\times 100/B$ (%)
CJ2	0.496	0.719	45
CJ4	0.41	0.734	79
CJ6	0.399	0.449	13
EJ-7	0.697	0.864	24

Table 6. CSI Summary for Trusses in T-Shaped Assembly Analyzed by TPM and SAP2000

Truss type	Max. CSI (CDP) (B)	Max. CSI (SDP) (C)	Percent difference $(C-B)\times 100/B$ (%)
T-1	0.971	0.393–0.905[a]	−60 to −7[a]
T-2	0.977	0.921–0.995[a]	−6 to +2[a]
TG-1	0.941	0.847	−10
GE	0.395	0.365–0.427[a]	−8 to +8[a]

[a]The range of the maximum CSI of trusses at each location and their percent difference.

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Table 7. CSI Summary for Trusses in L-Shaped Assembly Analyzed by TPM and SAP2000

Truss type	Maximum CSI (CDP)	Maximum CSI (SDP)	Percent difference (%)
T-1	0.977	0.872	−11
T-2	0.971	1.135	17
S-1	0.891	0.549	−38
S-2	0.977	0.877	−10
S-3	0.929	0.911	−2
S-4	0.856	0.842	−2
MH-1	0.901	0.707	−22
MHG-1	0.972	0.895	−8
TG-1	0.996	0.656	−34
HG8A	0.954	0.637	−33
EJ-7	0.697	0.864	24
EJ-8	0.96	0.721	−25
HJ-10	0.97	0.364	−62
HJ-11	0.845	0.559	−34

The CSI values of S-2 and MH-1 trusses located near the two-ply girder MHG-1 truss decrease. Another example is the EJ-8 truss, which is located next to the hip system and has a lower CSI when analyzed by the SDP;

5. Moreover, when trusses are located farther away from stiffer trusses, their CSI values based on the SDP do not change as much. The CSI values of S-3 and S-4 trusses located farther away from the MHG-1 truss change by only 2%;
6. Because of the location of EJ-7 truss (at Location 32), load from Subassembly *A* is transferred through the load-distributing element. Therefore, the CSI of EJ-7 at this location increases from 0.697 (CDP) to 0.864, i.e., by 24%. This shows that the modeling method also affects the structural behavior of the assembly; and
7. Trusses in an assembly model are connected by load-distributing elements. Based on the SDP, under applied loading, the load is transferred among trusses through load-distributing elements. Therefore, most trusses in the assembly have lower member forces, resulting in lower CSI values. For example, T-1 has a lower CSI when it is analyzed by SDP.

In summary, for the L-shaped assembly, the maximum CSI for most trusses decrease by 10–62% but CSI for one of the T-2 trusses increases. The decrease in CSI values for those trusses occurs because of the system effects, including reduced applied load and stiffer truss effects. These system effects are not observed by the CDP. This decrease in maximum CSI values can possibly contribute to reduced use of raw material.

In addition, the increase of the maximum CSI value of the aforementioned T-2 truss is 17% and brings it over 1.00, i.e., 1.135. This situation makes this truss unsafe in the assembly. This is not recognized by the CDP. Hence, the SDP provides improved safety of truss assemblies through advanced analysis.

CSI reduction also occurs in the complex assembly. Table 8 shows the maximum CSI of selected trusses in the complex assembly analyzed by the CDP and SDP, and their percent differences. Only trusses that have large CSI reduction (more than 10%) have been selected to show in Table 8. Their differences and reasons are discussed below:

1. The girder trusses, which are supporting other trusses, have a smaller tributary area as explained earlier. Each subassembly has girder trusses. Because girder trusses have a smaller tributary area in the SDP, their CSI values decrease. The CSI values of HG7A and HG8A trusses decrease by 15 and 19%, respectively. The maximum percent decrease in CSI of a girder truss occurs in the MHG-2 truss. It is because the MHG-2 truss is supporting other trusses from both sides of the truss. Its CSI decreases from 0.994 (CDP) to 0.721 (SDP), i.e., by 27%. Moreover, the same also occurs in the SG-1 truss;
2. Because some trusses in the complex assembly are spaced less than 0.61 m, their tributary area is smaller than those assumed by the CDP. Their CSI values decrease when analyzed by the SDP. This effect occurs in SG-1, S-9, S-10, EJ-5-1 (without overhang), EJ-5-2 (with overhang), CJ-4-1 (without overhang), and CJ-4-2 (with overhang) trusses;
3. Five hip systems are present in the complex assembly. As explained earlier, the Hip Jack (HJ) trusses in hip systems have no applied load. All HJ trusses in the complex assembly have lower CSI when they are analyzed based on the SDP; and
4. Another case of CSI reduction is that a truss that is located next to a stiffer truss (i.e., two-ply girder truss) attracting higher load, is less stiff and attracts less load, resulting in a lower CSI. This effect occurs in H9A, S-9, S-10, H10A, H12A, S-2, S-3, S-6, S-7, MH-1, S-6, S-7, S-8, and H10A trusses.

Table 8. Maximum CSI of Trusses in Complex Assembly

Truss type	Max. CSI (TPM) (B)	Max. CSI (SAP) (C)	Percent difference (%)
HG7A	0.99	0.844	−15
HG8A	0.961	0.776	−19
H9A	0.478	0.456	−5
MHG2	0.994	0.721	−27
SG-1	0.964	0.731	−24
S-9	0.856	0.734	−14
S-10	0.894	0.514	−43
EJ5-1	0.455	0.289	−36
EJ5-2	0.451	0.294	−35
CJ4-1	0.267	0.185	−31
CJ4-2	0.41	0.249	−39
HJ-10	1	0.638	−36
HJ-11	0.85	0.573	−33
HJ-10	1	0.621	−38
HJ-10	0.85	0.648	−24
HJ7	0.937	0.394	−58
S-3	0.929	0.79	−15
MH-1	0.88	0.616	−30
S-6	0.892	0.774	−13
S-7	0.819	0.667	−19
H10A	0.496	0.421	−15

In summary, for the complex assembly, the maximum CSI for all trusses decreases by 13–58%. In this case, it shows that the system effects, not recognized by CDP, provide advantages to truss assemblies by decreasing maximum CSI values. For most trusses in this assembly, it is possible to save raw material by either using lower grade material or providing higher spacing between trusses.

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The analysis of three actual truss assemblies using the SDP, instead of the CDP, has the following overall benefits: (1) improved truss system design by including system behavior directly; (2) increase safety through improved analysis; and (3) potential construction cost reduction.

Conclusions and Recommendations

Based on the SDP for 3D roof truss assemblies, the results show that there are system effects that are not accounted for by the CDP, but that could be directly included by analyzing 3D assembly models. The system effects observed by the SDP are as follows:

1. There are differences between total applied loads assumed by the CDP and by the SDP. This is because the CDP assumes that all trusses in an assembly have the same spacing (i.e., 0.61 m o.c.) leading to the same tributary width. The SDP, on the other hand, considers the actual tributary area among trusses in an assembly, resulting in more realistic applied load. This difference often leads to lower total applied load of trusses in an assembly;
2. Based on the CDP, there would be a displacement incompatibility for trusses supported by other trusses, but in the SDP, there is displacement compatibility throughout the system. While the CDP shows no deflection at the supports of trusses supported by a girder truss, the SDP shows that the same support deflects the same amount as the girder truss at that point. This is because the CDP always assumes that all trusses in the assembly are supported by walls. However, in real truss assemblies, some trusses may not be supported by walls. They are supported by other trusses, which are more flexible than those being supported by walls. The deflection at the ends of trusses supported by more flexible support (i.e., other trusses) usually increases when compared with those supported by stiffer supports (i.e., a wall). In the case of trusses supported by other trusses, the deflections obtained by the SDP are higher than those from the CDP;
3. In this study, the results also support the well-known fact that stiffer trusses attract more loads in the assembly models, which results in an increase in CSI values. The stiffer trusses consist of gable-end trusses in the T-shaped assembly model, and 2-ply trusses and the hip system in both the L-shaped and in complex assembly models;
4. CSI values based on the SDP are generally less than the CSI based on the CDP. CSI values reduced from 6 to 60% in the T-shaped assembly, from 2 to 62% in the L-shaped assembly, and from 5 to 58% in the complex assembly; and
5. However, in some cases, the CSI values may increase. For example, in the L-shaped assembly, the CSI of the T-2 truss at Location 1 increases from 0.971 (CDP) to 1.135 (SDP), i.e., by 17%. This increase in CSI is caused by the tributary area from the roof overhang, which was not included by the CDP. It shows that the SDP provides more realistic structural responses with improved analysis.

Based on this research study, there is an opportunity to improve the roof truss assembly design by capturing more realistic behavior of complex 3D roof truss assemblies used in the housing industry. Recommendations for future research studies are as follows:

1. Because the location of sheathing beams affects how loads are distributed among trusses in assemblies, further study should be conducted to determine a suitable way to represent the sheathing panels. For example, instead of using beam elements, plate elements could be introduced to represent roof-sheathing panels; and
2. To capture the structural behavior of a real complex roof assembly, further research studies should be conducted by testing a full-scale roof truss assembly. Although this technique requires a large budget, it is the best way to observe the structural behavior of such a complex structural system.

Practical Advice

Based on the results of this study the writers can offer the following practical advice for practicing engineers:

1. Trusses supported by other trusses (e.g., girder trusses) have higher deflection. Support truss (girder truss) should be analyzed first and deflection at the bottom chord panel points should be applied at the support of the truss which is going to be supported at that panel point before analyzing it. Proper detailing and inspection of this is needed so that trusses are supported by truss hangers and not just toe nailed into girder trusses;
2. Correct tributary area should be used for the gable end trusses. Some gable end trusses have a tributary area of 0.91 m due to overhang, whereas other trusses in the assembly may have a tributary area of less that 0.61 m; and
3. 3D analysis is needed to account for the proper behavior of hip truss assembly. Some of the lower chord members in 3D hip assembly may be in compression [Fig. 4(d) corner], which is not modeled by 2D analysis. Additional bracing for the bottom chord may be needed for the large hip truss assemblies.

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