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# TECHNICAL BULLETIN 18

## Evaluating the Accuracy of Moment Frame Design Models

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**Abstract:** Structural models that are used for design must reasonably represent the strength and stiffness of the structure. The accuracy of typical ETABS and RAM models for special moment frame systems was evaluated. For reduced beam section (RBS) and DuraFuse Frames (DFF) systems, ETABS and RAM models produced results that were similar to those obtained from rigorous models where connection geometries were modeled explicitly (using ANSYS). For SidePlate (SP) frames, the ETABS and RAM models based on SP modeling recommendations, had stiffnesses that were more than 1.3 times greater than the upper-bound stiffness determined from rigorous models. The artificial stiffness observed in the SP ETABS and RAM models was caused by inaccurate modeling assumptions recommended by SP. Modeling assumptions for SP frames should be corrected so that SP ETABS and RAM models have reasonably accurate stiffness.

### Executive Summary

The objective of this study was to evaluate the mathematical models (ETABS and RAM) that are commonly used in the design of three special moment frame systems [Reduced Beam Section (RBS), DuraFuse Frames® (DFF), and SidePlate® (SP)] and determine how accurately those models represent the actual stiffness of the moment frames.

To achieve the objective, sub-assembly stiffnesses obtained from rigorous FE models (using ANSYS), were compared with sub-assembly stiffnesses from typical design models (ETABS, RAM).

Key results from the study are summarized in the table below. For the RBS and DFF systems, the ratios of (ETABS Stiffness/ANSYS Stiffness) and (RAM Stiffness/ANSYS Stiffness) were in the range of 0.92 to 1.05, indicating that the RBS and DFF design models were accurate to within 8 percent.

Lateral Stiffness (k/in)

Sub-assembly	Weight (lbs)	ANSYS	ETABS	RAM	ETABS/ANSYS	RAM/ANSYS
RBS-1	2876	53.8	53.6	53.0	1.00	0.98
DFF-1	2876	63.6	66.0	66.9	1.04	1.05
SP-1	2876	74.6	93.1	93.3	1.25	1.25
RBS-2	3418	135.1	125.3	123.6	0.93	0.92
DFF-2	3418	153.2	159.3	160.8	1.04	1.05
SP-2	3418	165.0	217.1	228.8	1.32	1.39

For the SP systems, the ratios of ETABS stiffness/ANSYS stiffness and RAM stiffness/ANSYS stiffness were in the range of 1.25 to 1.39 when the ETABS modeling techniques recommended by SP and the RAM implementation from SP were employed, indicating errors of up to 39 percent. The errors observed in the SP design models were more than four times greater than the errors observed for the RBS or DFF models. The errors indicate that the modeling guidance given by SP with regards to panel zone stiffness and enhanced flexural stiffness at the ends of the beams was unreasonable for the cases considered.

The SP system has been marketed as being highly efficient, however those claims are based on ETABS and RAM models that inflate frame stiffness. When system efficiency is calculated as the actual sub-assembly stiffness (ANSYS) divided by the sub-assembly weight (including connection weight), SP sub-assemblies were 7-8 percent less efficient than comparable DFF or RBS sub-assemblies.

### Introduction

In seismic design of buildings, “a mathematical model of the structure shall be constructed for the purpose of determining member forces and structural displacements” (ASCE, 2016). For most structures, the mathematical model is developed in structural design software (i.e., ETABS, RAM, RISA). In design software, the primary elements of the structure (beams and columns) are considered

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explicitly in the design model while other elements, such as connections, are represented with springs, pins, rigid links, special elements, or fixed conditions. Overall, the mathematical model should reasonably represent the stiffness of the structure and the way forces are distributed.

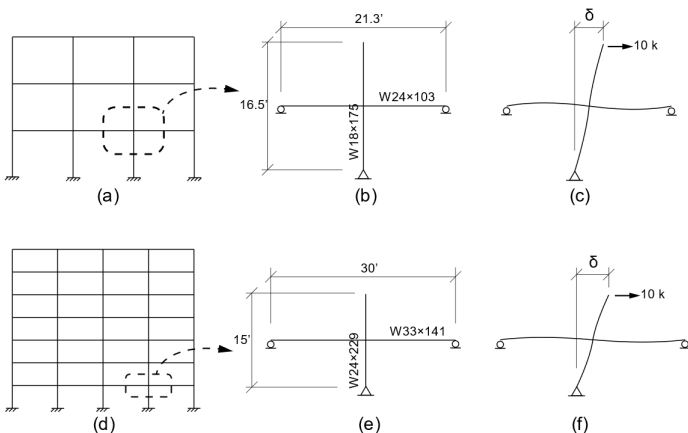
When designing special moment frames (SMFs), engineers can pick from a variety of proprietary and non-proprietary connections. The decision is often driven by economic considerations and a desire to minimize overall frame cost. Reasonable and consistent modeling assumptions must be made for all the connections for fair comparisons to be made. SMF connections that are often compared are: reduced beam section (RBS), DuraFuse Frames® (DFF), and SidePlate® (SP).

The objective of this study was to evaluate the mathematical models that are commonly used in the design of these three special moment frame systems (RBS, DFF, SP), and evaluate how accurately those design models represent the actual stiffness of the moment frames.

To achieve the objective, sub-assembly stiffness results from rigorous FE models, where connections were modeled explicitly (using ANSYS), were compared with stiffness results from design software (ETABS, RAM), where the connection plates were not modeled explicitly.

## Geometry and Connections

Sub-assemblies from two frames were used for the study. The first frame had W18×175 columns, W24×103 beams, a bay width of 21.3 ft, and a story height of 16.5 ft [Fig. 1(a)]. The second frame had W24×229 columns, W33×141 beams, a bay width of 30 ft, and a story height of 15 ft [Fig. 1(d)]. For comparing the stiffness of particular joints, sub-assemblies were evaluated, as is typically done in experimental testing. The two sub-assemblies used for the study are indicated in Fig 1(a)-(f), where beams and columns were cut at mid-span.



**Fig. 1** Sub-assembly geometries and sizes: (a)-(c) Sub-assembly 1; (d)-(f) Sub-assembly 2

Each sub-assembly was evaluated with different connections (RBS, DFF, SP). The connection designs for DFF and SP connections came from actual projects with beam and column sizes matching those shown in Fig. 1(b) and (e). The RBS connections were designed per AISC 358 (2016). Fig. 2 shows the details for each of the designs with member and plate sizes indicated.

Table 1 summarizes the total steel weight for each of the sub-assemblies. Weights varied for each case because of the different amounts of connection plate added at the joints and slight differences in the beam weights for the SP and DFF cases where the beams did not come all the way to the column face. For each group, the RBS version had the least weight because it had the least added plate. The SP sub-assemblies were 35 to 48 percent heavier than the RBS sub-assemblies with the same beam and column size.

**Table 1** Sub-assembly weights

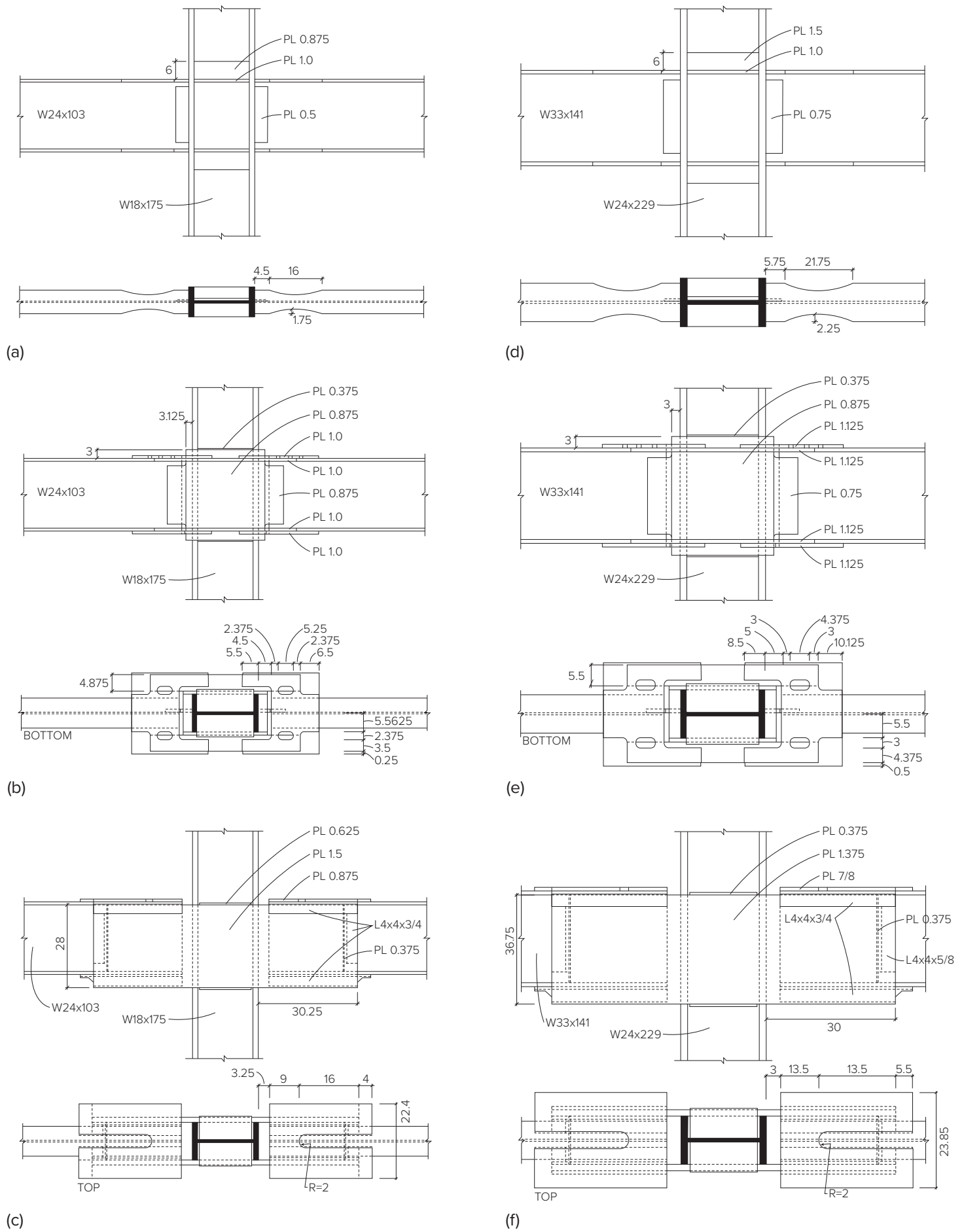
Sub-assembly	Weight (lbs)				Total
	Column	Beam	Doubler/ Cover Plates	Other Connection Material	
RBS-1	2876	2007	152	119	5154
DFF-1	2876	1930	397	918	6121
SP-1	2876	1973	1917	883	7650
RBS-2	3418	3874	434	185	7910
DFF-2	3418	3758	624	1343	9144
SP-2	3418	3805	2464	989	10676

## Rigorous Modeling Techniques (ANSYS)

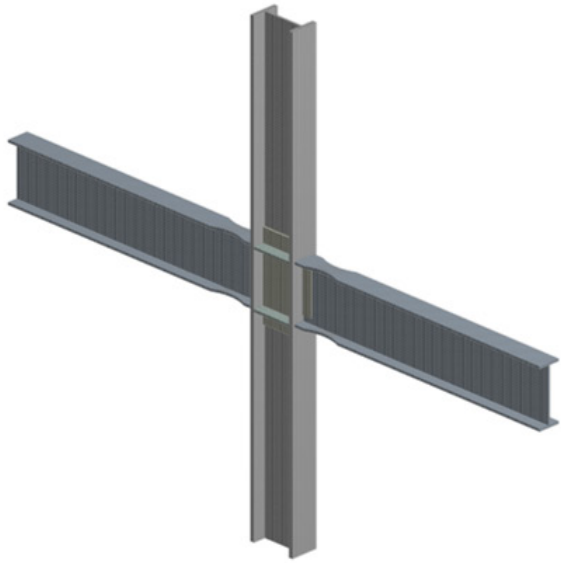
The software ANSYS Mechanical (2020) was used to develop rigorous FE models to provide a basis for evaluating the design models (ETABS, RAM). The same ANSYS modeling techniques were used for all cases.

Modeling techniques suited the purpose of evaluating upper-bound elastic stiffness. The models were not used to predict bolt-slip, yielding, post-yield response, or stress concentrations. For all models, the steel material had a modulus of elasticity of 29,000 ksi and Poisson's ratio of 0.3. Inelastic material properties were not defined. Since the purpose of the models was to evaluate upper-bound elastic stiffness, bolted surfaces were tied to each other, generously representing conditions prior to bolt slip for DFF and SP. Individual bolts and bolt holes were not modeled explicitly. Solid elements with 20 nodes (SOLID186 in ANSYS) were used for all the models with a maximum element size of 1 in. Weld geometry was not represented explicitly in the models. Plates were assumed fused to each other where they made contact.

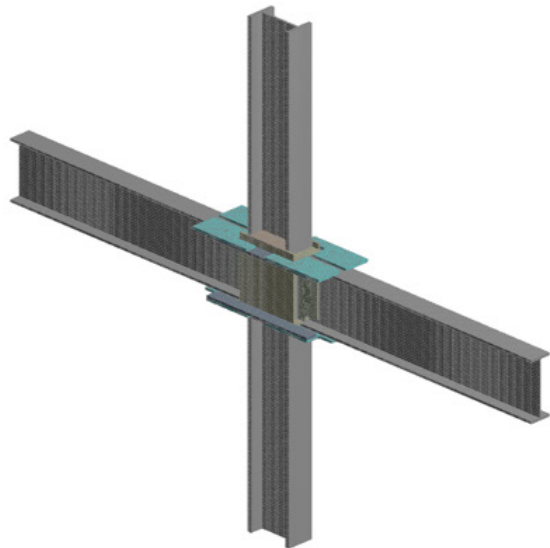
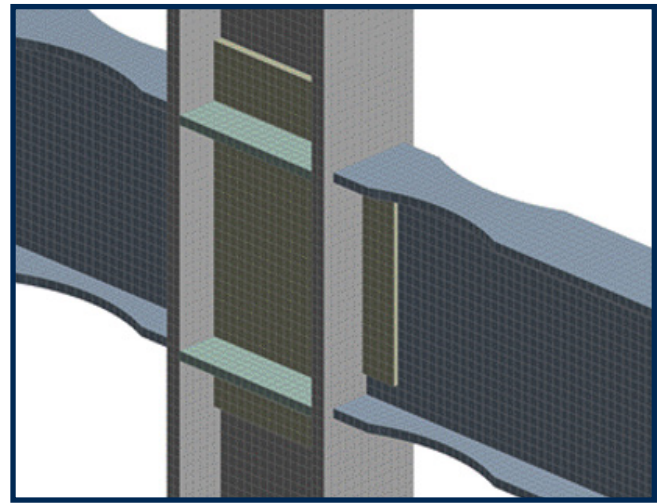
Boundary conditions and loads were applied at the beam and column ends. Fig. 3 (next page) shows the finite element models for the sub-assemblies with W18×175 columns. The boundary conditions at the beam and column ends matched those shown in Fig. 1 (c) and (f). Nodes at the end cross-sections of the beams and column were constrained so that pinned boundary conditions could be applied at the center-points of the cross-section without causing stress concentrations. An arbitrary lateral load of 10 kips was applied to all the models [Fig. 1(c) and (f)].



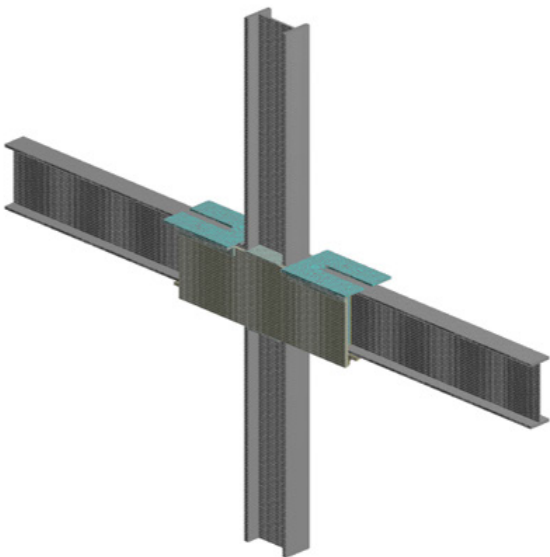
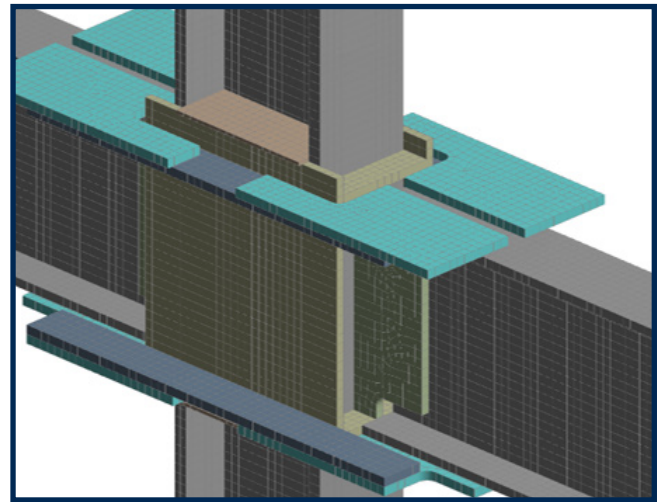
**Fig. 2** Connection details: (a) RBS-1; (b) DFF-1; (c) SP-1; (d) RBS-2; (e) DFF-2; (f) SP-2



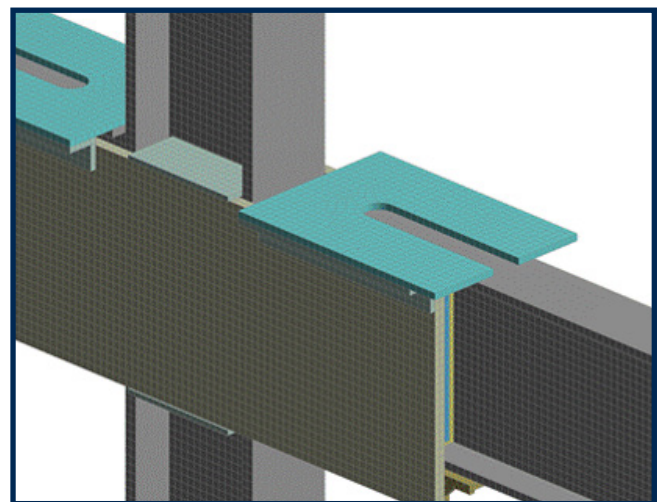
(a)



(b)



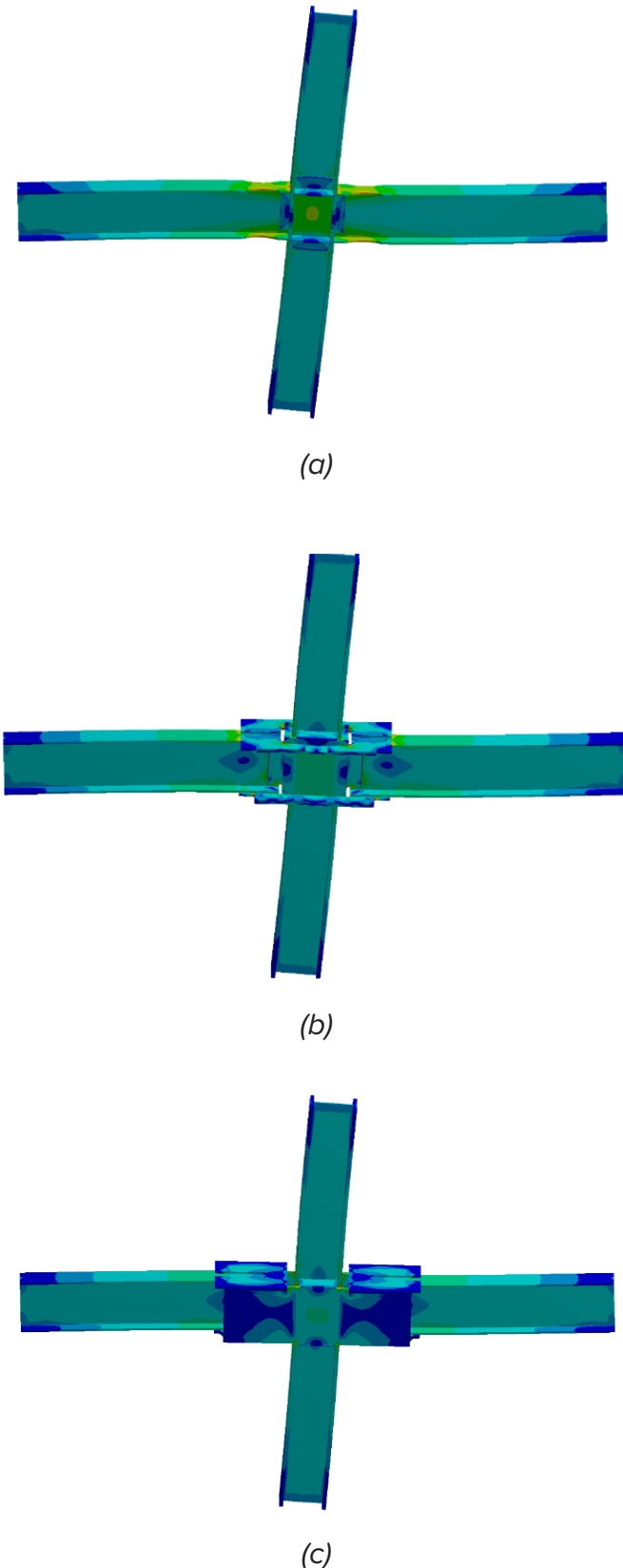
(c)



**Fig. 3** Finite element models that considered connection plates and geometry explicitly: (a) RBS-1; (b) DFF-1; (c) SP-1

## Results from Rigorous FE Analysis (ANSYS)

The ANSYS models were used to determine sub-assembly stiffness. Fig. 4 shows the models for RBS-1, DFF-1, and SP-1 under lateral loading (deformed shape amplified 100×, von Mises stress shown).



**Fig. 4** ANSYS models subjected to lateral loading: (a) RBS-1; (b) DFF-1, (c) SP-1

Table 2 summarizes results from the ANSYS analyses. The first column in Table 2 is the total sub-assembly weight from Table 1. The second column in Table 2 indicates the elastic stiffness of the sub-assembly, calculated as the lateral force applied in the analysis (10 kips) divided by the lateral displacement,  $\delta$  [see Fig. 1(c) and (f)]. The last column is an efficiency metric.

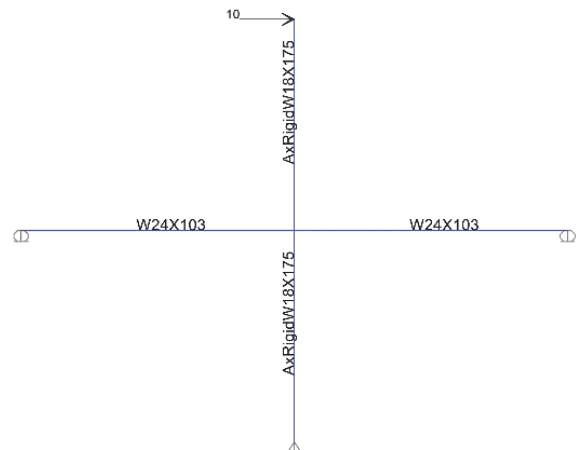
**Table 2** Results from rigorous finite element analyses (ANSYS)

Sub-assembly	Weight (kips)	ANSYS Stiffness (k/in)	ANSYS Stiffness/Weight (k/in/k)
RBS-1	5.15	53.8	10.44
DFF-1	6.12	63.6	10.39
SP-1	7.65	74.6	9.75
RBS-2	7.91	135.1	17.07
DFF-2	9.14	153.2	16.76
SP-2	10.68	165.0	15.46

As would be expected, the heavier sub-assemblies in each group had the greatest stiffness. To evaluate sub-assembly efficiency, the stiffness of each was divided by the weight (last column of Table 2). The second group (RBS-2, DFF-2, SP-2) had higher efficiencies than the first because of the deeper column and beam sections. Within each group, DFF and RBS had comparable material efficiency, while SP sub-assemblies were 7 to 8 percent less efficient.

## ETABS Modeling Techniques

The sub-assemblies that were modeled in ANSYS were also modeled in ETABS (CSI, 2020). Fig. 5, illustrates a typical model, with RBS-1 shown. The ETABS models had the geometry, loading, and boundary conditions indicated in Fig. 1(b) and (e). The specific ETABS modeling techniques for each connection type are summarized next.



**Fig. 5** Typical ETABS model (RBS-1 shown)

### RBS Modeling in ETABS

The RBS sub-assemblies were modeled with a modified beam section in the region of the RBS cut, using the built-in ETABS feature (CSI, 2020). The RBS cut dimensions (a, b, and c) in the ETABS models matched those shown in the details [Fig. 2(a) and 2(d)]. The panel zone flexibility was represented through centerline modeling (Rigid zone

factor = 0), as is common practice (Hamburger et al., 2016).

#### DFF Modeling in ETABS

The DFF sub-assemblies were modeled in ETABS following the guidance from McCall and Richards (2020). The cross-sectional properties of the beam were constant along the clear-span and a standard fully restrained (FR) moment connection was assumed at the beam-column connection. The panel zone was modeled with a scissor spring and rigid end offsets, with the spring stiffness determined per Charney and Marshall (2006). The thickness of the DFF cover plates, as indicated in Fig. 2(b) and (e), was combined with the thickness of the column web in determining the panel zone spring stiffness.

#### SP Modeling in ETABS

The SP sub-assemblies were modeled in ETABS following the guidance from SP (SidePlate, 2017). The panel zone was modeled as perfectly rigid (rigid zone factor = 1.0 for end offsets, no panel zone spring). The moment of inertia of the beam was increased by a factor of 3 in the connection region by using the non-prismatic beam section feature in ETABS. The stiffened connection region extended 30.25 in. from the column face for SP-1, and 30 in. from the column face for SP-2, based on the plate dimensions [Figure 2(c) and (f)].

## ETABS Results and Discussion

Table 3 summarizes ETABS results, with ANSYS results provided for comparison. The ratio of the ETABS stiffness and ANSYS stiffness (last column of Table 3) was used to evaluate the accuracy of the ETABS models.

**Table 3** Results from ETABS analyses

Sub-assembly	Weight (kips)	ETABS Stiffness (k/in)	ANSYS Stiffness (k/in)	ETABS/ANSYS
RBS-1	5.15	53.6	53.8	1.00
DFF-1	6.12	66.0	63.6	1.04
SP-1	7.65	93.1	74.6	1.25
RBS-2	7.91	125.3	135.1	0.93
DFF-2	9.14	159.3	153.2	1.04
SP-2	10.68	217.1	165.0	1.32

#### RBS Discussion

For the RBS sub-assemblies, the ETABS model for RBS-1 was more accurate than the model for RBS-2 because of panel zone assumptions. The ETABS/ANSYS ratio of 1.00 for RBS-1 (Table 3) indicated remarkable accuracy for the ETABS model that employed centerline modeling. This was somewhat lucky, since centerline modeling is known to be somewhat conservative for some geometries (Hamburger et al., 2016) and somewhat non-conservative for others. The ETABS/ANSYS ratio of 0.93 for RBS-2 (Table 3) indicated a conservative error of 7 percent in the ETABS model. Most of this error came from the centerline modeling assumption to represent the panel zone. As compared to RBS-1, the panel zone of RBS-2 had greater depth and stiffness, but centerline modeling does not appropriately reward deeper panel zones. It makes sense that RBS-2 had more error than RBS-1.

#### DFF Discussion

For the DFF sub-assemblies, there was good agreement between the ETABS and ANSYS models. The ETABS/ANSYS ratio of 1.04 for DFF-1 and DFF-2 indicated an error of only 4 percent in the ETABS models for both cases (Table 3).

As with the RBS models, the errors in the DFF ETABS model were from the panel zones. Previous studies have shown that even when panel zones are represented explicitly with springs, results do not exactly match experiments or continuum FE models (Downs, 2002). Even with panel zone springs, panel zone flexural deformations are not accounted for (Downs, 2002) and cover plates are assumed to be fully effective (Kim and Engelhardt, 2002), resulting in some error.

The errors for the DFF ETABS models were similar to the RBS ETABS models and both were reasonable for design. The accuracy of the DFF ETABS models confirmed that the modeling guidance from McCall and Richards (2020) was valid.

#### SP Discussion

The results for SP-1 and SP-2 were alarming. The ETABS/ANSYS ratios of 1.25 and 1.32 for SP-1 and SP-2 indicated errors of up to 32 percent in the ETABS models (Table 3). These errors were much worse than those observed for RBS or DFF models, indicating problems with the SP modeling recommendations (SidePlate, 2017).

Part of the error in the SP ETABS models stemmed from the rigid panel zone assumption. To quantify that error, modified ETABS models for SP-1 and SP-2 were developed with the panel zones modeled per the recommendations in the literature (Charney and Marshall, 2006), including the thickness of the SidePlates with the column web thickness in determining the panel zone stiffness. With reasonable panel zone modeling, the errors for SP-1 decreased from 25 percent to 11 percent, and the errors for SP-2 decreased from 32 percent to 19 percent indicating that about half of the errors were due to inaccurate panel zone modeling.

The basis for the SP rigid panel assumption deserves discussion. Most testing of SP connections has involved exceptionally deep and heavy beams and columns and one-sided connections (AISC, 2016). When exceptionally deep and heavy beams and columns are used and connections are one-sided, panel zone deformations may be small enough to neglect; however, SP has extended this assumption to all geometries (SidePlate, 2017). This study indicates that such an approach is clearly unreasonable for W18 $\times$  and W24 $\times$  columns.

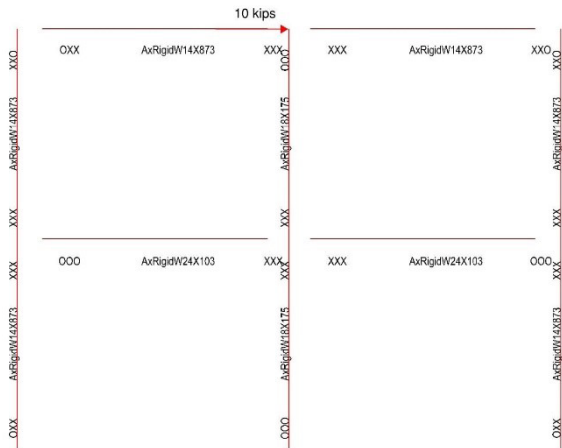
The other source of error in the SP ETABS models (SP-1 and SP-2) was the flexural stiffness adjustment for the beams in the connection region. SP recommends using 3 $\times$  the beam stiffness in the connection region (SidePlate, 2017). That assumption would only be valid if the entire cross-section were attached to the face of the column. In the actual SP connection, none of the beam end is attached to the face of the column [Fig. 2(c) and (f)]. Since only some of the elements are attached, the cross-sectional area is

not fully effective in the connection region, making the approach inaccurate.

The net result of the SP modeling guidelines was that the ETABS models had inflated stiffnesses, up to 1.32 times greater than the upper-bound stiffness from the ANSYS models. Such design models are unreasonable considering the relative accuracy of models for other moment frames.

## RAM Modeling Techniques

The same sub-assemblies were analyzed in RAM Structural System (Bentley, 2020). The RAM models had the geometry, loading, and boundary conditions indicated in Fig. 1. Rigid beam elements were used to “frame” the sub-assemblies. Fig. 6 illustrates a typical RAM model. The specific RAM modeling techniques for each connection type are summarized below.



**Fig. 6** Typical RAM model (RBS-1 shown)

### RBS Modeling in RAM

The built-in RAM features to model RBS connections were employed. The RBS properties for the beams were set to match those shown in Fig. 2. The panel zone flexibility for the RAM RBS models was represented through centerline modeling (no rigid end zones).

### DFF Modeling in RAM

The built-in RAM features to model DFF connections were employed. RAM modeled the DFF connection with a standard FR connection and standard beam moment of inertia along the entire clear span. RAM modeled the DFF panel zone with a Scissor spring and rigid end offsets (Charney and Marshall, 2006). The cover plate thickness and dimensions used in the RAM model matched those in Fig. 2.

### SP Modeling in RAM

The built-in RAM features to model SP connections were employed. No user input for the connection parameters was required/permitted. RAM automatically assigned properties to the beams and panel zone.

The RAM modeling procedures (Bentley, 2020) are conceptually the same as the SP recommendations for ETABS modeling (rigid end zones, no panel zone spring,

stiffened regions at the ends of the beams). The difference is that, in RAM, the dimensions of the stiffened region of the beam and the multiplier for the stiffened region are “calculated based on the clear span length of the framing beams and its size” and are not reported because they are considered proprietary (Bentley, 2020).

## RAM Results and Discussion

Table 4 summarizes RAM results, with ETABS and ANSYS results provided for comparison. The third column lists the stiffness of the sub-assemblies from RAM. The fourth column compares the RAM stiffness from the ETABS stiffness previously discussed. The fifth lists the stiffness for the ANSYS models (as reported in Table 2). The last column is the ratio of the RAM stiffness and ANSYS stiffness, which can be used to evaluate the accuracy of the RAM models.

**Table 4** Results from RAM Analyses

Sub-assembly	Weight (kips)	RAM	ANSYS		RAM/ANSYS
		Stiffness (k/in)	RAM/ETABS	Stiffness (k/in)	
RBS-1	5.15	53.0	0.99	53.8	0.98
DFF-1	6.12	66.9	1.01	63.6	1.05
SP-1	7.65	93.3	1.00	74.6	1.25
RBS-2	7.91	123.6	0.99	135.1	0.92
DFF-2	9.14	160.8	1.01	153.2	1.05
SP-2	10.68	228.8	1.05	165.0	1.39

### RBS Discussion

The RAM/ANSYS ratio was 0.98 for RBS-1 and 0.92 for RBS-2 (Table 4), indicating conservative errors of 2 to 8 percent for the RBS RAM models. As previously discussed, the errors were primarily the result of centerline modeling and consistent with other studies.

The RBS RAM results were within 1% of the RBS ETABS results for both RBS-1 and RBS-2 (see RAM/ETABS in Table 4), which was expected since they were both based on the same theory.

### DFF Discussion

For the DFF connections, there was good agreement between the RAM and ANSYS models. The RAM/ANSYS ratios were 1.05 (Table 4) for DFF-1 and DFF-2 indicating a maximum error of 5 percent, which would be reasonable for design. As with the ETABS models, the primary source of errors was the panel zone.

The RAM results were within 1% of the ETABS results for both DFF-1 and DFF-2 (see RAM/ETABS in Table 4), which was expected since they were both based on the same theory.

### SP Discussion

The RAM/ANSYS ratio was 1.25 for SP-1 and 1.39 for SP-2 (Table 4), indicating errors of up to 39 percent. The sources of the errors were panel zone modeling and the stiffened regions at the ends of the beams.

The RAM results were within 1% of the ETABS results for SP-1 (see RAM/ETABS Table 4), which was expected since they were both based on the same theory. However, for

SP-2, the results from RAM were significantly different from those obtained from ETABS. Since RAM does not report the parameters used for SP modeling, it is difficult to pinpoint the source of the added inaccuracy. It is likely that the connection length that RAM assumed was greater than the actual connection [Fig. 2(f)], which was from a real project.

The net result of the SP RAM modeling parameters was that the SP RAM models had inflated stiffnesses that were 1.25 to 1.39 times greater than the upper-bound stiffnesses. These errors are unreasonable given the relative accuracy of models for other moment frame connections.

## Summary, Conclusions, and Recommendations

The objective of this study was to evaluate the mathematical models (ETABS and RAM) that are commonly used in the design of three special moment frame systems (RBS, DFF, SP) to see how accurately those models represent the actual stiffness of the moment frames.

Six sub-assemblies were used for the study, representing two unique frame geometries in combination with the three different connection types. DFF and SP connection designs came from actual projects. The elastic stiffness of the sub-assemblies was determined using ANSYS, ETABS, and RAM. The ANSYS models explicitly accounted for all the connection plates and provided an upper-bound stiffness (all the plates were assumed fused at bolted interfaces). The ETABS and RAM models employed typical assumptions that are used for design. As part of the study, the efficiency of connections was evaluated using the ANSYS model results.

The study supports the following conclusions:

- DFF provided 7 to 8 percent more stiffness, per pound of material, than SP frames with same column and beam depth.
- The RAM and ETABS implementations for the RBS connection resulted in models that were accurate to within 8 percent when panel zones were represented through centerline modeling.
- The modeling procedures that DFF recommends resulted in design models (ETABS/RAM) that were accurate to within 5 percent of the stiffness from rigorous ANSYS models.
- The modeling procedures that SP recommends for ETABS, and that are built into RAM, resulted in errors of up to 39 percent.
- The rigid panel zone assumption for the SP connections was shown to be unreasonable for the sub-assemblies that were studied. When SP panel

zones were modeled using reasonable methods in ETABS, errors were reduced by about half.

- The SP recommendation to increase the flexural stiffness of the beams by 3× in the connection region was shown to exaggerate the stiffness well beyond the theoretical upper bound determined by rigorous models (ANSYS).
- The modeling procedures, that SP recommends for ETABS and that are built into RAM, exaggerate stiffness and would be unreasonable for design for the cases that were studied (W18× and W24× columns with W24× and W30× beams).

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