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SC Wall Compression Behavior: Interaction of Design and Construction Parameters

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Abstract

Modular steel-plate composite (SC) construction involves pre-fabricated steel modules that are transported to the site, assembled and then filled with concrete. The construction parameters (concrete casting height, etc.) and casting sequence for these modular walls may vary, leading to small but permanent stresses and deformations (or imperfections). These geometric imperfections, combined with the variations in SC wall design and detailing parameters (such as steel and concrete grades, tie bar spacing, faceplate slenderness), could influence the compressive behavior and capacity of the SC walls. This paper explores the effects of imperfections and design parameters on the axial compression capacity of the SC walls. The analysis procedure involves simulating the effects of initial imperfections, construction sequence, etc., followed by axial compressive loading up to failure. Parametric studies are conducted to evaluate the effect of variability in steel grades, faceplate slenderness, and height of concrete pour on the compression behavior of SC walls. The analysis results indicate that the compression behavior of SC walls (for nuclear facilities) is dominated by concrete. Faceplates for SC walls meeting the requirements of AISC N690s1 perform adequately (yield in compression before buckling) for concrete pour heights up to 30 ft. However, the concrete pour height and plate slenderness affect the faceplate waviness tolerance, and need to be addressed in the analysis. The performance of specimens with 36 ksi faceplates is acceptable for the current configuration of ties, but needs to be explored for different configurations. Future studies will further evaluate the effects of tie spacing and configuration, and concrete grades.

1. Introduction

Steel-plate composite (SC) construction consists of concrete infill sandwiched by steel plates (faceplates) on two sides. The faceplates are connected to each other by means of tie bars. Composite action between the faceplates and concrete infill is provided by steel anchors. A typical SC wall is shown in Fig. 1 (from AISC 2015). SC structures have been used extensively in the third generation of nuclear power plants, and are also being considered for small modular reactors (SMRs) of the future and commercial construction. SC construction is employed for

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labyrinthine structures (with cross-walls) typical to nuclear structures. SC wall piers (SC construction without any flange walls) are typically used as shear walls in Department of Energy (DOE) type nuclear facilities and commercial construction. SC wall piers are also inherently present in safety-related nuclear facilities where the walls have large openings. AISC N690s1 (AISC 2015) provides requirements for design of SC walls in safety-related nuclear facilities. ASCE 7 (ASCE 2010) and AISC 341 (AISC 2016) seismic provisions provide requirements for design of composite steel-plate shear walls (C-PSW), with and without boundary elements, in seismic regions.

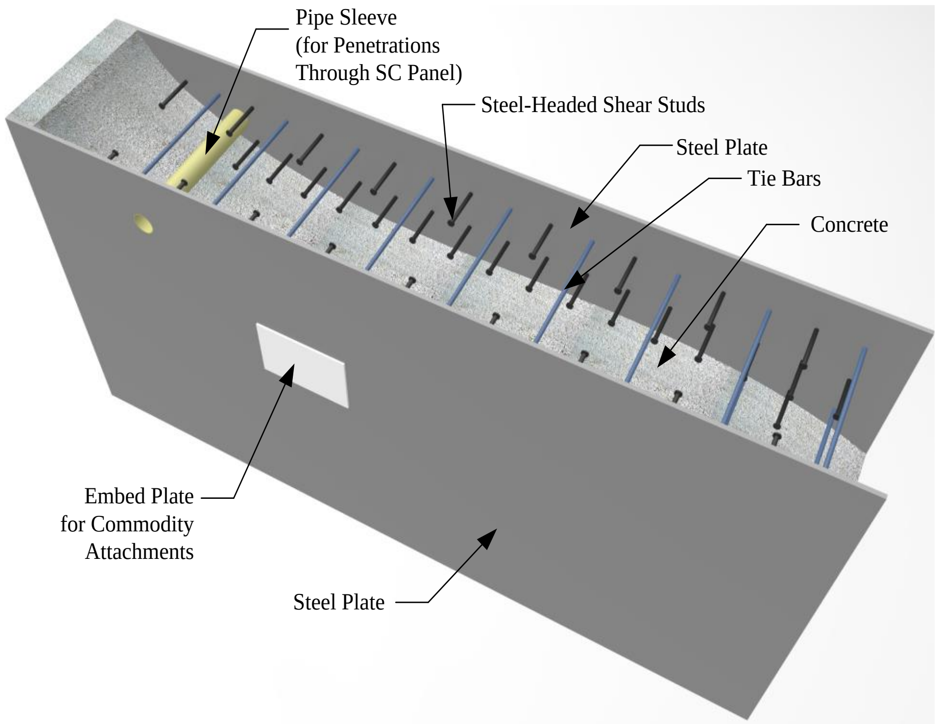


Figure 1. Typical SC Wall section (from AISC 2015)

Modular SC construction comprises of various phases, which typically include:

a) Fabrication of empty SC panels and sub-modules (steel assemblies) in the shop,
b) shipping the empty modules to the field,
c) combining the panels and sub-modules into modules, and erecting them at the site, and
d) casting concrete.

The steel faceplates have initial imperfections before being assembled in to empty modules. These imperfections may be exacerbated during the fabrication, transportation and erection of the empty modules. The concrete casting pressure would further amplify these imperfections. The final faceplate imperfections may influence the buckling behavior of the faceplates and affect the compression capacity of the SC walls. Additionally, the size of the modules, the construction sequence, the mode of lifting, transportation and erection of the modules, are generally different for each project due to a number of variables and constraints involved. The dynamic nature of the construction procedures, leading to variation in the faceplate imperfections needs to be addressed in the design of the SC walls.

AISC N690s1 provides the following requirements in this regard:

a) concrete strength (4ksi to 8 ksi) and faceplate strength (50 ksi to 65 ksi),
b) provide faceplate slenderness limit (to prevent faceplate from buckling before compression yielding), and
c) provide dimensional tolerances for faceplates during fabrication, assembly, before casting, and after casting of concrete. The faceplate waviness requirement limits the out-of-plumbness of faceplates after concrete casting.

The high variability in construction procedures, and unforeseen deviations from the procedure, may lead to the some of the AISC N690s1 requirements being violated (or may render it impossible to meet the requirements). Confirmatory or reconciliatory analysis may be required for these SC walls. The authors (Bhardwaj and Varma 2016) have previously devised an analysis procedure for simulation of the construction sequence for SC wall panel sections. The simulation includes the effect of initial imperfections and concrete casting pressure on the behavior of the SC wall panel sections. The procedure can be employed to evaluate the effects of faceplate slenderness, faceplate waviness, tie spacing (spaced at section thickness or half the section thickness), concrete pour height, faceplate yield strength, and concrete compressive strength on the compression behavior of the SC wall panel sections. This paper presents an outline of the procedure and implements it to evaluate the interaction of construction and design parameters, and the effects of the interaction on the compression behavior of the SC walls.

2. Background

Zhang et al. (2014) studied the effect of shear connector (and tie) spacing on the faceplate buckling and composite behavior of SC walls. Faceplate slenderness requirement (Eq. A-N9-2 of AISC N690s1) and faceplate waviness requirement (Eq. NM2-1 of AISC N690s1) are based on studies by Zhang et al. (2014). However, the faceplate slenderness requirement may sometimes not be met due to design or construction constraints. Additionally, the faceplate waviness requirement may lead to faceplate imperfections of magnitude up to two times the faceplate thickness. The study by Zhang et al. (2014) also did not consider the effect of parameters such as concrete pour height, tie bar spacing, etc. on the compression behavior of SC walls.

Bhardwaj and Varma (2016) developed an analysis procedure to evaluate the effects of construction sequence, and construction and design parameters, on the compression behavior of SC walls. The procedure is presented in Fig. 2, and has not been discussed in detail herein for brevity. This paper presents the results of parametric studies conducted using the procedure.

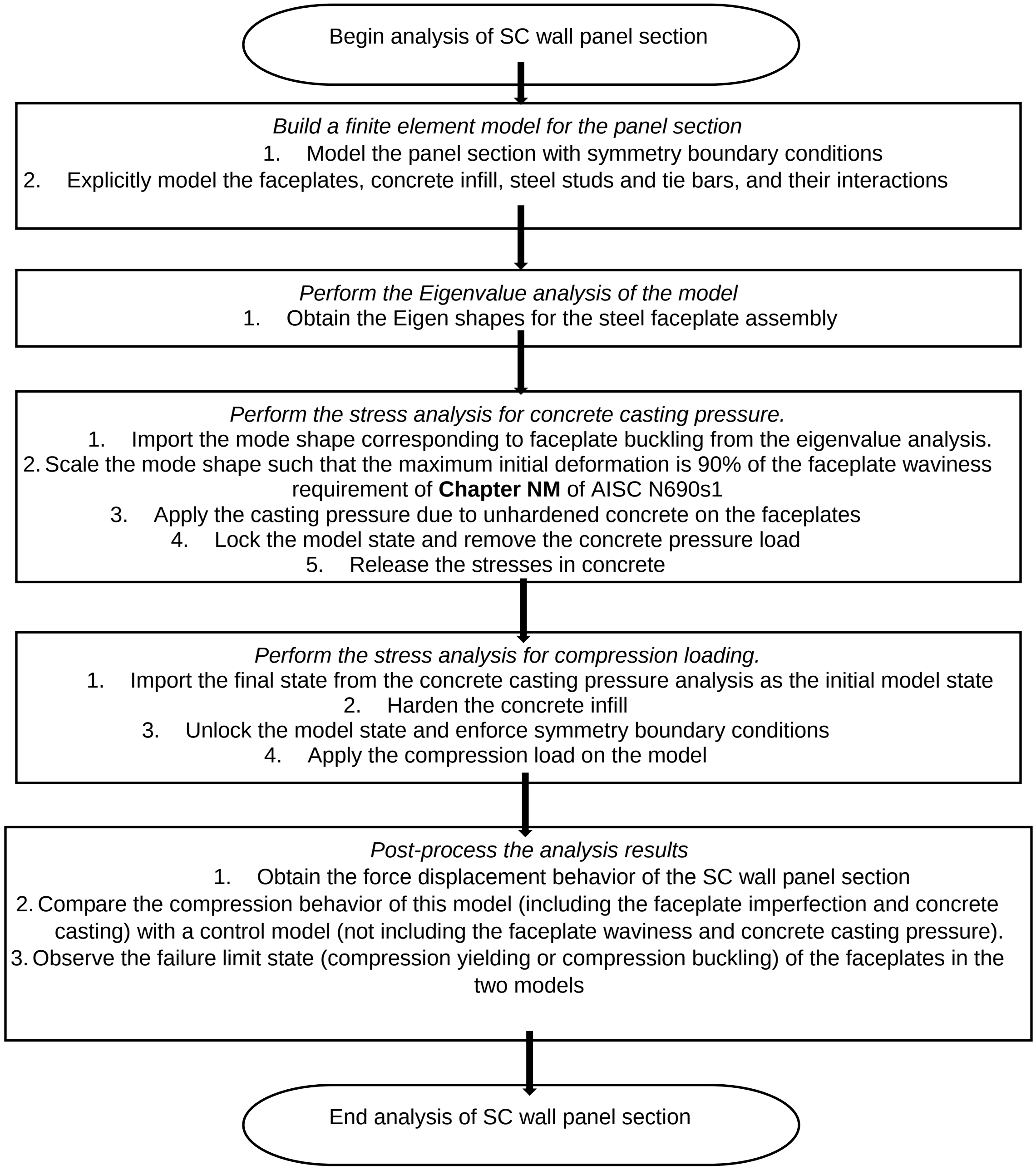


Figure 2: Procedural flowchart for analysis of SC wall panel sections for compression loading (including imperfection and concrete casting pressure) (from Bhardwaj and Varma 2016)

3. Parametric Studies

Table 1 presents the details of SC specimens modeled and analyzed for this study. The specimen nomenclature is A-B-C-D, where A is the steel grade (in ksi), B is the concrete grade (in ksi), C is the multiplier for slenderness limit specified in AISC N690s1, and D is the concrete pour height (in ft.). The parametric study matrix has been designed to evaluate the effect of change in the faceplate slenderness, and concrete casting height on the stability and compression behavior of SC walls. The initial imperfection for all the specimens has been kept at 90% of the faceplate waviness limit prescribed by AISC N690s1. For this study, tie bars are spaced at half the section thickness, round bars are used as studs and ties (considered welded to the faceplates). As observed from Column J of Table 1, this study focuses on lightly reinforced SC walls. Some of the specimens have been designed to not meet the requirements of AISC N690s1, with an intent to evaluate the behavior of specimens that violate code requirements. The analysis models and methodology are consistent with the description in Bhardwaj and Varma (2016).

Comparison of analysis results from models 1, 2, and 6 (and 7, 8, and 11) will demonstrate the effect of varying the faceplate slenderness for 50 ksi steel (and 36 ksi steel). Models 2, 3, 4, 5 (and 8, 9, 10) will establish the effect of concrete pour height on the imperfection and buckling behavior of the faceplates. The effect of imperfections on the specimens will also be evaluated individually by comparing them with control specimen. The analysis models have not been discussed in this paper. Parameters for a typical analysis model (50-6-1-X) are presented in Fig. 3.

Table 1: Parametric study matrix

A	B	C	D	E	F	G	H	I	J	K	L	M	N
Model No.	Specimen Name	Fy (ksi)	tp (in.)	Concrete Grade (ksi)	Slenderness requirement	Stud Spacing (in.)	Tie Spacing (in.)	Section Thickness t_{sc} (in.)	rho ($2t_p/t_{sc}$)	Section Dimensions (in.)	Initial Imperfection ($0.9xf_w$), in.	Tie Dia (in.)	Concrete Pour Height (ft.)
1	36-6-0.8-10	36	0.2	6	$0.8(E/Fy)^{0.5}$	4	12	24	0.017	36	0.270	0.5	10
2	36-6-1-10	36	0.2	6	$1(E/Fy)^{0.5}$	5	15	30	0.013	45	0.270	0.6	10
3	36-6-1-20	36	0.2	6	$1(E/Fy)^{0.5}$	5	15	30	0.013	45	0.270	0.6	20
4	36-6-1-30	36	0.2	6	$1(E/Fy)^{0.5}$	5	15	30	0.013	45	0.270	0.6	30
5	36-6-1-60	36	0.2	6	$1(E/Fy)^{0.5}$	5	15	30	0.013	45	0.270	0.6	60
6	36-6-1.5-10	36	0.125	6	$1.5(E/Fy)^{0.5}$	5	15	29.85	0.008	45	0.270	0.6	10
7	50-6-0.8-10	50	0.2	6	$0.8(E/Fy)^{0.5}$	3	9	18	0.022	27	0.270	0.5	10
8	50-6-1-10	50	0.2	6	$1(E/Fy)^{0.5}$	4	12	24	0.017	36	0.270	0.6	10
9	50-6-1-20	50	0.2	6	$1(E/Fy)^{0.5}$	4	12	24	0.017	36	0.270	0.6	20
10	50-6-1-30	50	0.2	6	$1(E/Fy)^{0.5}$	4	12	24	0.017	36	0.270	0.6	30
11	50-6-1.5-10	50	0.2	6	$1.5(E/Fy)^{0.5}$	7	21	42	0.010	63	0.270	0.5	10

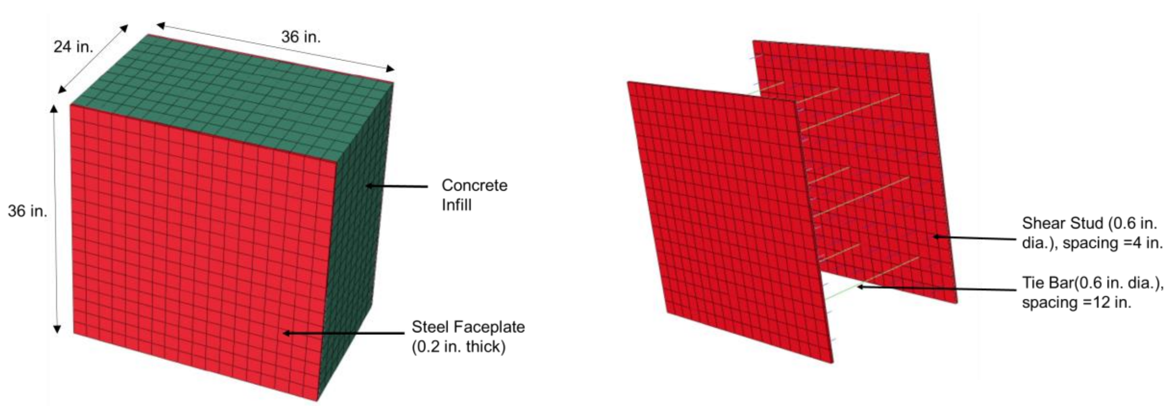


Figure 3. Typical Model Parameters

4. Results

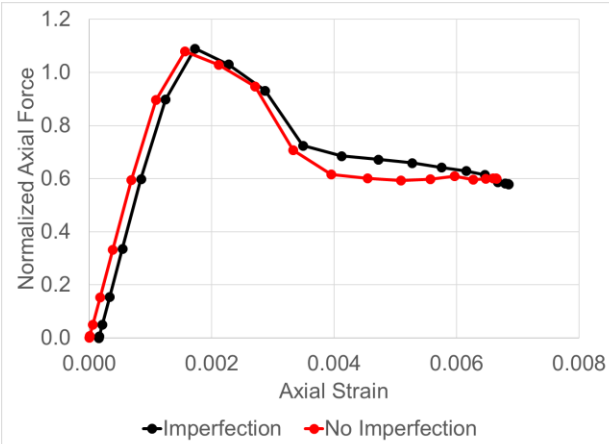
The models mentioned in Table 1 are analyzed and post-processed to evaluate the effect of variation in construction and design parameters on the compression behavior of SC walls. The specimens with imperfections are compared with the corresponding control specimens (without any imperfections) to assess any changes in axial capacity and stiffness. Effective strain-strain curves for steel and concrete are obtained to evaluate how the imperfections alter the steel and concrete behavior in the specimen. The concrete pour height is expected to reduce the faceplate contribution to axial capacity and increase the faceplate waviness (faceplate deflection between tie bars). The faceplate center deflection is plotted versus the axial strain to assess the effect of concrete pour height on the faceplate waviness. The observations from the models are discussed in the following sub-sections.

4.1 Axial Capacity and Stiffness: Effect of Slenderness

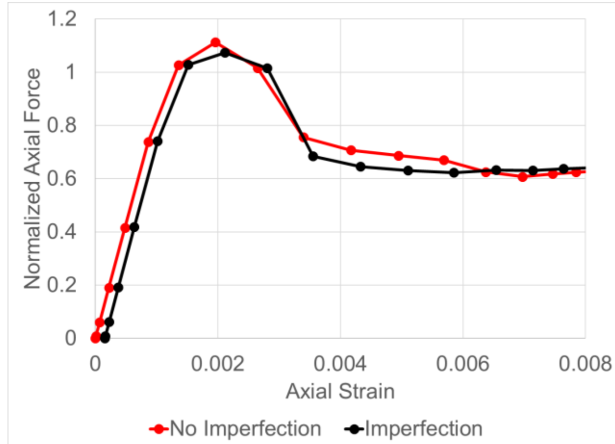
Fig. 4 presents the normalized axial force (axial force normalized with the expected axial capacity) versus the axial strain plots for models with different slenderness and 36 ksi steel faceplates. The sub-figures compare the capacity and stiffness of models (with constant slenderness) with and without imperfections. It is observed that the introduction of imperfections (due to faceplate waviness and 10 ft. concrete pour height) does not significantly affect the axial capacity or stiffness of the specimens (the reduction in capacity is less than 5%). Comparing the sub-figures reveals that the change in slenderness also does not significantly affect the capacity and stiffness of the specimens. The same trend is observed for specimens with 50 ksi faceplates (Fig. 5). The specimen 50-6-1.5 does seem to have a slightly larger reduction in capacity, but it is still less than 5%. The peak value in the plots is greater than one because a factor of 0.85 is considered in the concrete contribution to axial capacity, whereas this reduction is not applicable to force obtained from ABAQUS (Simulia 2014).

The change in slenderness is expected to change the buckling behavior of the faceplates. AISC N690s1 requires a faceplate slenderness (s/t_p) of less than or equal to $\left(E/F_y\right)^{0.5}$, where s is the stud spacing, t_p is the faceplate thickness, E is the modulus of elasticity and F_y is the steel yield strength. The faceplate slenderness requirement ensures that the faceplate yields in compression before buckling. In order to evaluate the behavior of specimens violating the faceplate slenderness requirements, the stress distribution in the faceplates is assessed. Fig. 6 presents the von mises stress at peak load for specimens 50-6-1.5 and 36-6-1.5. The faceplates of specimen 50-6-1.5 buckle before yielding. Specimen 36-6-1.5 faceplates do yield before buckling but that may be due to the tie spacing or other geometric parameters. Therefore, for faceplates not complying with the slenderness requirements, the yielding of faceplates before buckling cannot be ensured.

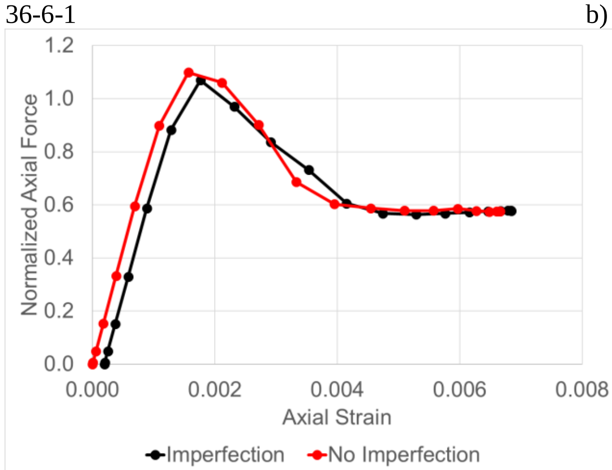
However, the slenderness of faceplates does not significantly affect the compression behavior of the specimens as it is dominated by concrete behavior (steel contribution to the compression capacity is less than 10%). The effect of slenderness of faceplates may be higher for specimens with higher reinforcement ratios (the specimens in this study have relatively low reinforcement ratios).



a) 36-6-1

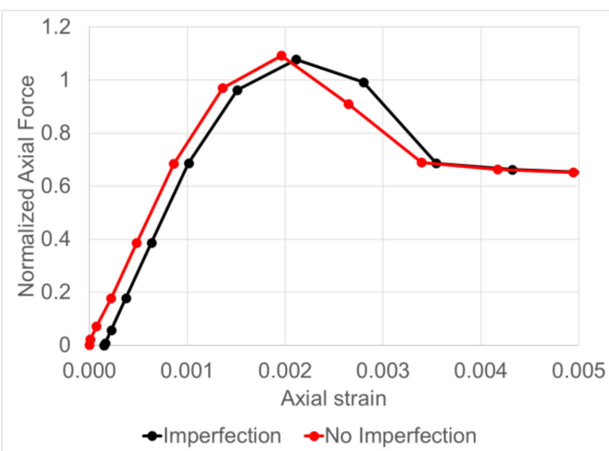


b) 36-6-0.8

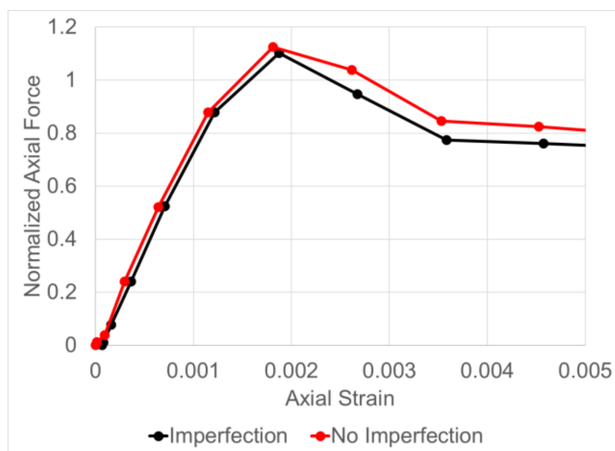


c) 36-6-1.5

Figure 4. Effect of slenderness on axial capacity (36 ksi steel)

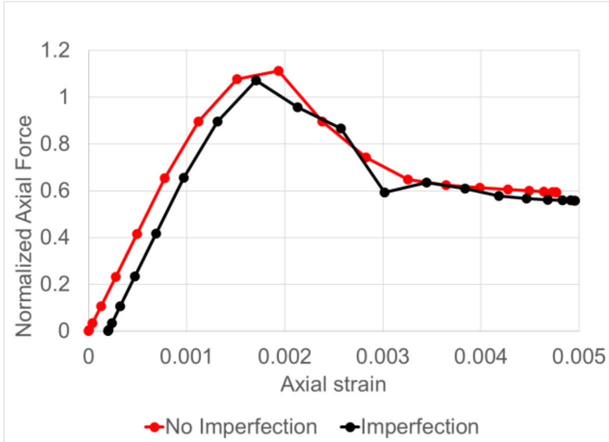


a) 50-6-1



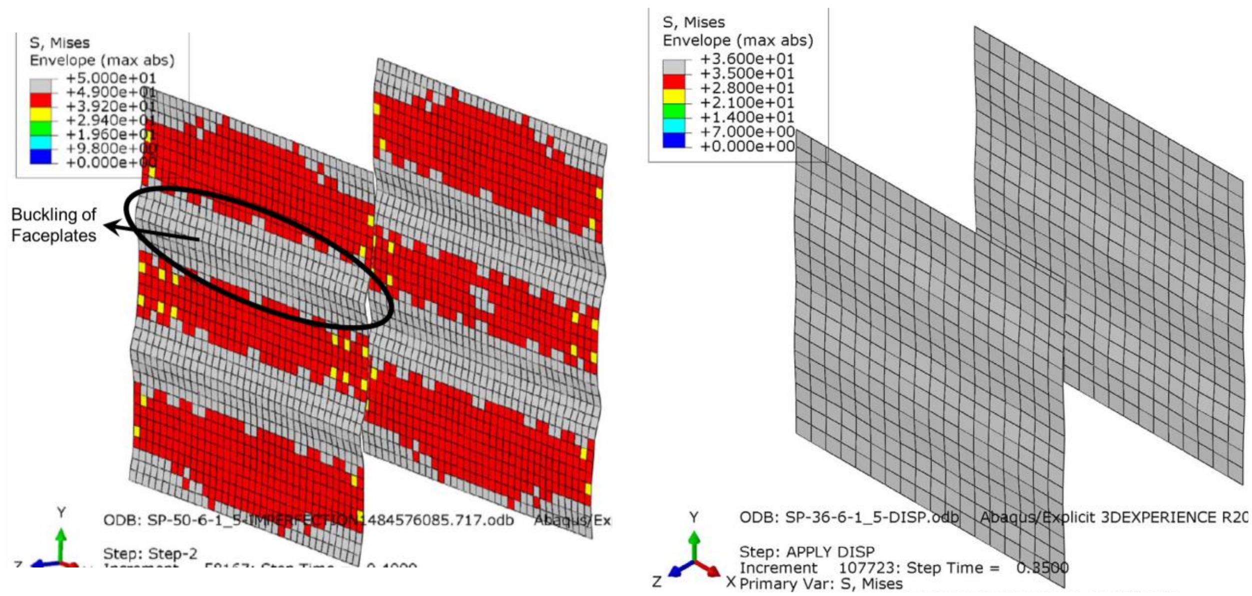
b) 50-6-0.8

Figure 5. Effect of slenderness on axial capacity (50 ksi steel)



c) 50-6-1.5

Figure 5. Effect of slenderness on axial capacity (50 ksi steel)

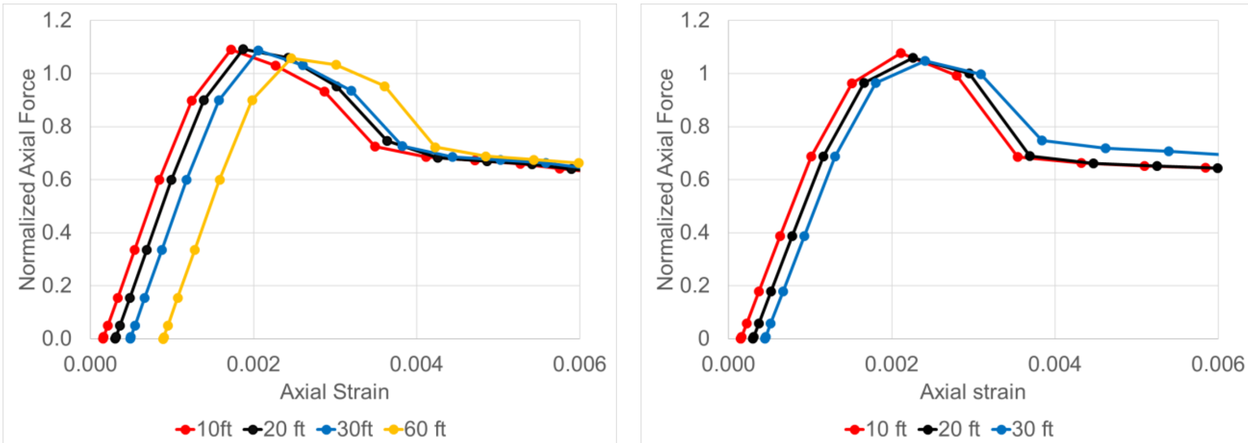


a) 50-6-1.5 b) 36-6-1.5

Figure 6. Von Mises stress in specimens not meeting slenderness criteria

4.2 Axial Capacity and Stiffness: Effect of Concrete Pour Height

Fig. 7 shows the normalized axial force versus axial strain plots for 36 ksi and 50 ksi specimens that meet the slenderness requirements (36-6-1 and 50-6-1). The plots compare the behavior for different concrete pour heights. There is no significant reduction in capacity or stiffness for different concrete pour heights up to 30 ft. (there is residual strain in concrete from the casting pressure analysis which seems to cause an initial axial strain and slight degradation in the capacity for the analysis with higher concrete pour height). The reduction in capacity increases to about 5% when the concrete pour height is 60 ft. and these cases seem to warrant further investigation (especially for higher reinforcement ratio specimens). The behavior (limited impact of concrete pour height) is limited to this tie configuration for SC walls (round ties welded to the faceplates), as this causes the faceplates behavior under concrete casting pressure to be similar to flat plates on column supports. There is stress concentration in the plates around the ties and stress redistribution takes place once the faceplates and concrete are loaded in compression. The behavior may be different for other tie configurations (e.g., angles, flat bars), or configurations with stiffened tie rows (with ribs, etc.). The effects of concrete pour height are expected to be higher for specimens that do not meet the slenderness requirements of AISC N690s1.



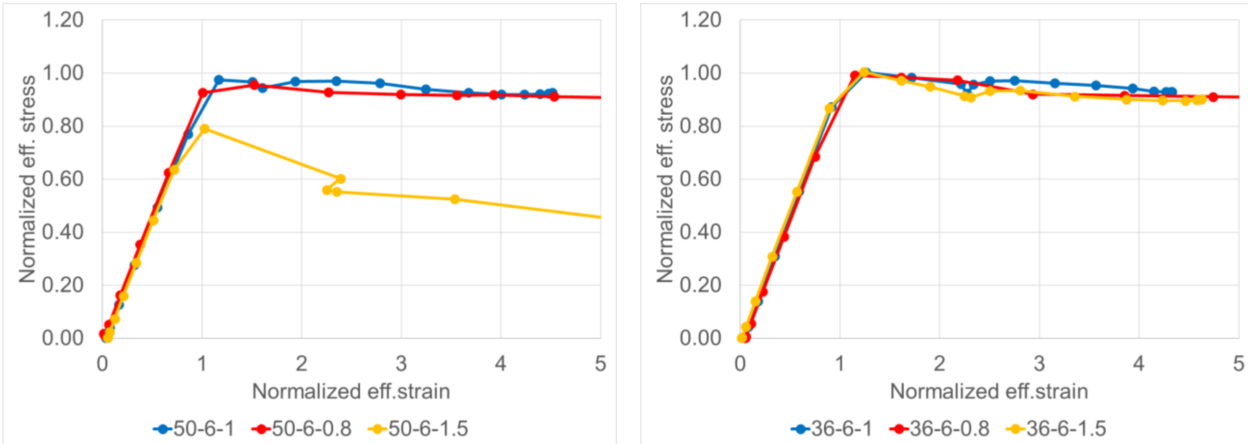
a) 36-6-1 b) 50-6-1

Figure 7. Effect of concrete pour height on the axial capacity and stiffness

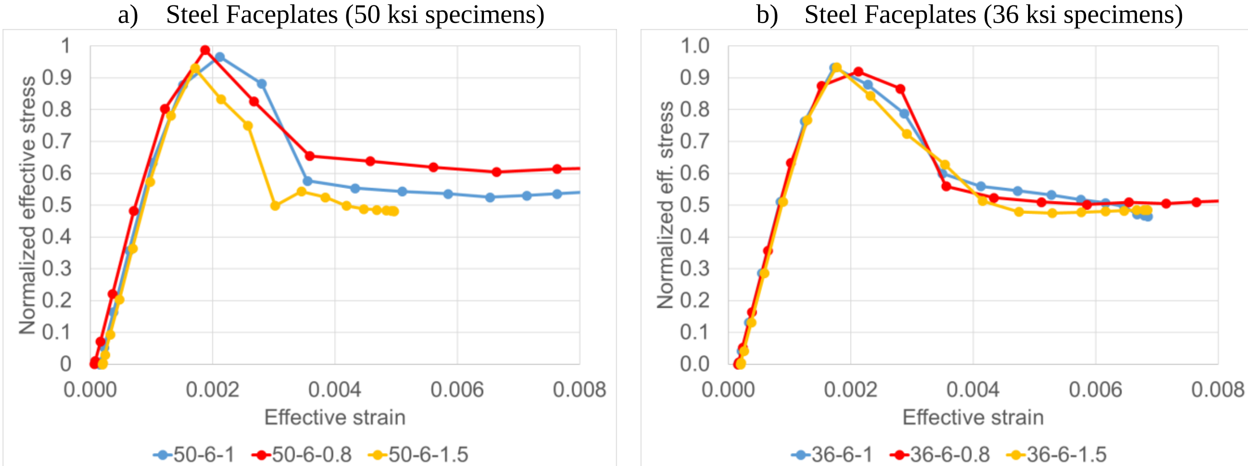
4.3 Effective Stress-Strain Curves: Effect of Slenderness

The previous sections indicate that for the specimens in this study, the compression behavior is dominated by concrete. The faceplate behavior under compression is not apparent from the overall behavior. Therefore, the individual response of concrete infill and faceplate to compression loading needs to be evaluated. Fig. 8 presents the effective stress-effective strain curves for steel and concrete for specimens (36 ksi and 50 ksi) with different slenderness ratios. For steel faceplates (Fig. 8a and 8b), the effective stress is calculated by taking the average stress of the faceplate elements that are at the center of two adjacent rows of studs where buckling is expected to occur. The stress is normalized with the yield stress of the faceplates (36ksi or 50 ksi). The effective strain is the strain between the adjacent rows of studs where buckling is expected to occur. The strain is normalized by the yield strain for the faceplates. For concrete (Fig. 8c and 8d), the effective stress is the compression force in concrete divided by the cross-section area of concrete. The stress in normalized by the concrete compressive strength (6ksi). The concrete effective strain is the compressive strain in the specimen. The steel and concrete material models are consistent with the ones discussed in Bhardwaj & Varma (2016).

Fig. 8a and 8b illustrate that the faceplate effective stress-effective strain behavior is consistent with the material model for the steel (elastic-perfectly plastic), with the effective stress reaching the yield stress and staying consistent thereon (the slight degradation in the stress may be due to second order effects). The exception is the stress-strain behavior for 50-6-1.5, where the stress starts degrading before reaching the yield stress. This is consistent with the observation in Fig. 6a, which shows that the faceplates buckle before yielding (the effective stress does not reach yield stress). It is also observed that the faceplate effective stress- effective strain behavior is consistent for specimens with slenderness ratios meeting the requirements of AISC N690s1. Similarly, in Fig. 8c and 8d, it is observed that the concrete effective stress-effective strain behavior is consistent with the concrete uniaxial behavior input (Popovic’s model) for specimens with slenderness ratios meeting the requirements of AISC N690s1. For specimen 50-6-1.5, the buckling of the faceplates seems to hinder the ability of concrete to get up to the compressive strength.



a) Steel Faceplates (50 ksi specimens) b) Steel Faceplates (36 ksi specimens)

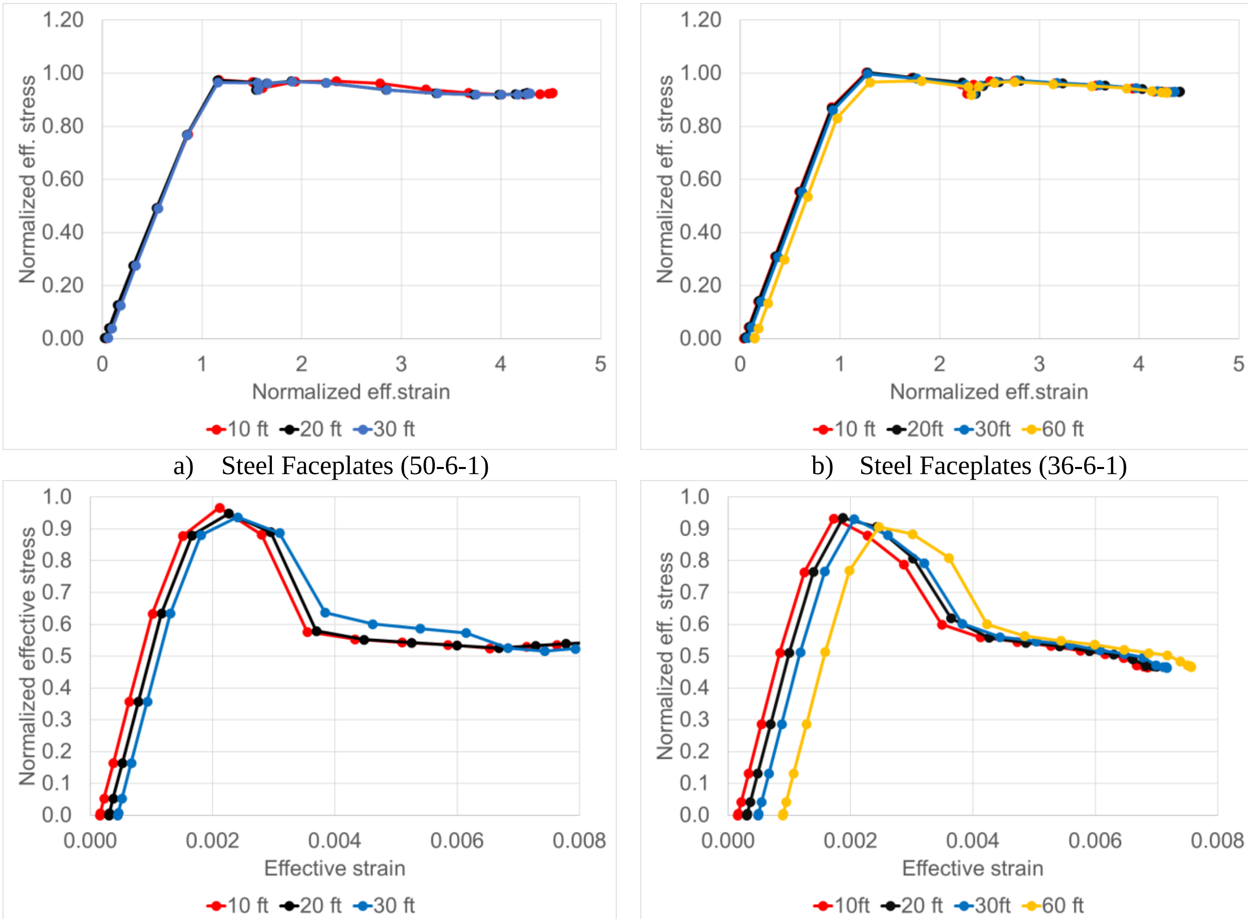


c) Concrete Infill (50 ksi specimens) d) Concrete Infill (36 ksi specimens)

Figure 8. Steel and concrete effective stress strain curves for specimens with different slenderness limits

4.4 Effective Stress-Strain Curves: Effect of Concrete Pour Height

Fig. 9 presents the steel and concrete effective stress-effective strain plots for specimens (50-6-1 and 36-6-1) subjected to concrete casting pressure corresponding to different pour heights. It is observed that the pour heights up to 30 ft. do not have a significant effect on the steel and concrete material behavior. However, the specimen with a pour height of 60 ft. does seem to not be able to get up to compressive strengths for both steel and concrete. Construction procedures demanding atypical concrete pour heights warrant additional analysis. As discussed earlier, the effects of concrete pour height may be significant for specimens with other tie arrangements, higher reinforcement ratios, and specimen with higher slenderness ratios.



a) Steel Faceplates (50-6-1)

b) Steel Faceplates (36-6-1)

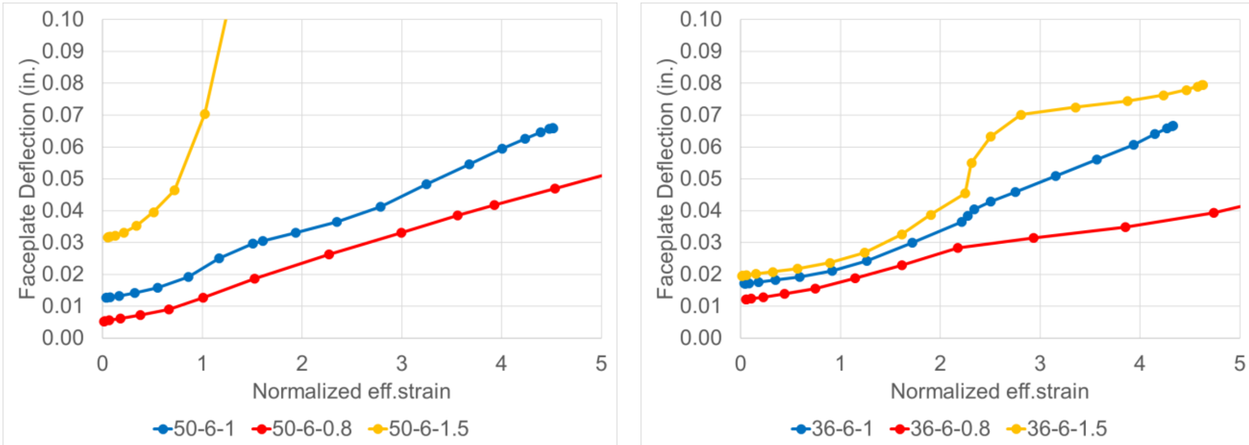
c) Concrete Infill (50-6-1)

d) Concrete Infill (36-6-1)

Figure 9. Steel and concrete effective stress strain curves for specimens subjected to different concrete pour height pressures

4.5 Faceplate Deflection: Effect of Slenderness

The faceplates inherently have some initial imperfections that may be amplified by various construction activities. These analyses limit those imperfections to $0.9f_w$, where f_w is the faceplate waviness limit specified by AISC N690s1 (0.3 in. for these cases). Additional analysis may need to be performed to determine the out-of-plumbness of faceplates due to erection and transportation, before the concrete casting. Fig. 10 presents how the faceplate deflection varies due to concrete casting, and as compression loading is applied. The faceplate deflection is measured at center line between two adjacent rows of studs. The faceplate deflection is plotted against the normalized effective axial strain in the faceplates (measured between two adjacent rows of studs). The initial faceplate deflection (when strain is zero) is the deflection due to concrete casting pressure (corresponding to concrete pour height of 10 ft. for all cases). This faceplate deflection (when added to the initial imperfection, 0.27 in., for these specimens) needs to meet the faceplate waviness requirement (0.3 in. for these specimens) of AISC N690s1. It is observed that all specimens, with exception of 50-6-1.5, meet the faceplate waviness requirements. Specimen 50-6-1.5 has a faceplate waviness greater than 0.3 in. The faceplate deflection for this specimen increments rapidly as the faceplates start to buckle. Additionally, it is observed that the rate of increase of faceplate deflection under compression loading increases as the faceplates becomes slender.

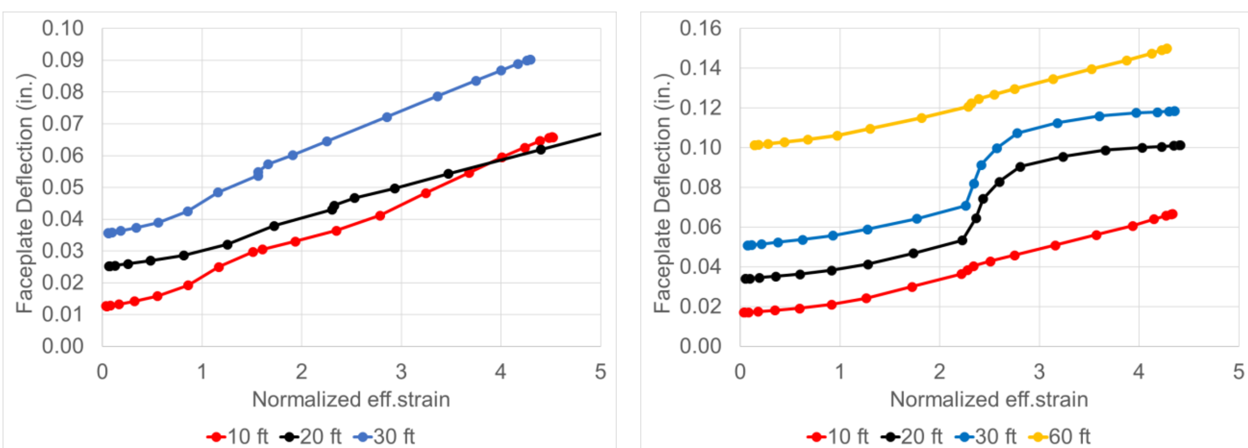


a) 50 ksi Faceplate Specimens b) 36 ksi Faceplate Specimens

Figure 10. Effect of slenderness on faceplate deflection

4.6 Faceplate Deflection: Effect of Concrete Pour Height

Since the initial imperfection for all the specimens has been kept the same ($0.9f_w$), the faceplate waviness of the specimens will be affected by the concrete pour height. Fig. 11 presents the variation in faceplate deflection for specimens that meet the slenderness requirements of AISC N690s1 (50-6-1 and 36-6-1) as the concrete pour height is changed. It is observed that the concrete pour height directly impacts the faceplate waviness (faceplate deflection at zero effective strain). For 50-6-1 specimens (Fig. 11a), faceplate waviness limit is exceeded for a concrete pour height of 30 ft. For 36-6-1 specimens (Fig. 11b), the faceplate waviness limit is exceeded for concrete pour heights of 20ft., 30ft., and 60ft. Thus, it is observed that concrete pour height has a significant effect on the faceplate waviness and deflection, and needs to be considered in the analysis, consistent with the construction procedure.



a) 50-6-1 b) 36-6-1

Figure 11. Effect of concrete pour height on faceplate deflection

5. Conclusions

The following deductions are made from the results discussed above.

a) The compressive behavior of SC walls is dominated by concrete. The steel contribution to compression capacity is generally less than 10% of the total capacity. Therefore, changes in steel behavior (e.g., buckling of faceplates), have small to negligible effect on the compressive capacity. However, the faceplate compression behavior may affect the failure mode of the SC wall. The contribution of faceplates to compression capacity and behavior may be significant for specimens with higher reinforcement ratios, and other configuration of ties (namely larger tie spacing).
b) For specimens satisfying the slenderness requirements of AISC N690s1, the faceplate yields in compression before buckling. The buckling of faceplates may precede the faceplate yielding for specimens not complying with AISC N690s1 slenderness requirements.
c) For this configuration of ties, the concrete pour height up to 30 ft. does not have a significant influence on the compressive behavior of the specimens. Any further increase in the pour height needs to be adequately addressed in the analysis.
d) Concrete pour height and slenderness of the specimen affect the faceplate waviness of the specimen. This is an important dimensional tolerance required by AISC N690s1, and needs to be considered in the analysis. The faceplate waviness will be affected by the construction procedure and sequence, the slenderness, and tie spacing of the specimens.
e) For the current configuration and spacing of ties (spaced at half the section thickness), compression behavior of 36 ksi steel faceplates (not permitted by AISC N690s1) meeting other requirements of AISC N690s1 is adequate. Different configurations need to be investigated to further explore the compression behavior of SC walls with 36 ksi faceplates.

6. Future Work

This paper presents parametric studies considering one type of tie configuration. Other possible tie configurations (angles, flat bars, ties rows reinforced with ribs) need to be considered. The steel material models used in this study are elastic-perfectly plastic. The steel stress-strain curve can be updated to include hardening and strength degradation. The tie bars (and stud) connections to the faceplates are modeled using connector elements. The behavior of these connector elements in tension is considered elastic, and can be updated based on relevant recent research. The faceplate waviness tolerance will vary with the construction sequence and procedure (e.g., assembly, lifting, erection procedures). These can also be integrated into the procedure developed by the authors to develop a holistic solution to address how construction and design parameters interact to affect the compression behavior of SC walls.

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