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Application of an Inclined Shear Reinforcing Assembly for Slab-Column Connections

Mario Glikman, Gabriel Polo, Oguzhan Bayrak, and Trevor D. Hrynyk

Synopsis: The performance of slab-column connections has been critically studied over the last several decades by researchers aiming to better understand the behavior of flat slabs subjected to punching shear loading conditions. As a result, the use of slab shear reinforcement has emerged as a practical strategy to improve both the strength and ductility of reinforced concrete flat slabs.

The primary objective of this research study was to investigate the behavior of reinforced concrete slab-column connections employing an inclined shear reinforcement system comprised of deformed steel reinforcing bars. Results are presented from an experimental program conducted at the Ferguson Structural Engineering Laboratory of The University of Texas at Austin. The tests were aimed at establishing the merits and limitations of the shear reinforcement system, and it was found that a premature failure attributed to inadequate shear reinforcement anchorage controlled the performance of the strengthened slabs. The performance of the slabs constructed with the inclined reinforcement system is compared to that of slabs reinforced with more conventional, vertically-oriented, shear reinforcement. Lastly, the influence of the observed anchorage-driven failures were examined in the context of estimated slab shear resistances developed from provisions and analysis methods currently available for reinforced concrete flat slabs.

Keywords: flat slabs; inclined shear reinforcement; punching shear; slab-column connection; two-way shear.

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INTRODUCTION

Reinforced concrete (RC) flat slab systems are widely used in modern building infrastructure. Historically, these types of structures were designed with large transitioning capitals to facilitate the flow of forces from the slab to the supporting columns. In recent decades, flat slabs without capitals (i.e., flat plates) have become more prevalent, mainly due to efficiencies associated with their simple forms and reduced construction requirements. However, in contrast to their simplified geometries, the load transfer mechanisms involved in RC flat plates can be rather complex. Three-dimensional loading conditions consisting of combined flexure and shear often lead to increased load resistance demands, particularly in regions forming slab-column connections.

Among the primary objectives in the design of two-way reinforced concrete (RC) slab systems is the requirement to mitigate and/or prevent the onset of premature brittle punching shear failures, prior to significant flexural yielding. Such undesirable failure modes have been shown to occur in flat plates that have been exclusively reinforced in their planar directions and, in several instances, have been deemed responsible for the onset of total structure failure (Mitchell and Cook 1984). Two approaches have traditionally been used to enhance the punching shear strength of RC slabs: i) alteration of the slab thickness and/or column sizing such that increased shear forces can be resisted by the concrete comprising the slab, or ii) by way of supplemental shear reinforcement oriented through the thickness of the slabs (i.e., in the out-of-plane direction). The latter is often favored as the addition of shear reinforcement does not result in any significant increase in structure mass and it provides a means of locally tailoring regions of increased slab shear capacity while maintaining uniform slab thickness.

Slab shear reinforcement consisting of vertically oriented deformed steel reinforcing bars are typically provided by way of steel links, individual stirrups, or cages of continuous bent reinforcing bars which are sized and custom-tailored to the configuration of the longitudinal bars comprising the slab-column connections. Although effective in carrying out-of-plane shear, the use of such reinforcement schemes presents significant installation challenges and requires additional design considerations to ensure that adequate anchorage is provided (e.g., anchorage for stirrups/caged shear reinforcement is typically provided by way of intersecting longitudinal reinforcing bars). To ease installation and simplify detailing requirements, the use of prefabricated shear stud rail systems have emerged as a favorable alternative to the reinforcing schemes noted above. Consisting of smooth steel studs which are mechanically anchored to the concrete by way of anchor heads and/or welded steel rails, prefabricated stud assemblies are designed to independently develop required end anchorage; hence, such systems do not require customized fabrication in accordance with the configuration of the longitudinal reinforcing bars comprising slab-column connections.

The shear response of RC structural members has been studied extensively in recent decades. Among the more significant findings from the related research and investigations performed, it has been shown that the shear strength of RC is highly dependent on the ability of cracked RC to develop tensile stresses between crack locations through concrete tension stiffening (Vecchio and Collins 1986; Bentz 2005) and on concrete's ability to transfer local shear stresses along crack surfaces through aggregate interlock (Walraven 1981). Both shear resisting mechanisms rely heavily on bond stress development between the steel reinforcing bars and the surrounding concrete and both mechanisms are functions of the crack widths developed under shear stresses.

Overview of Relevant Literature

A large volume of experimental research has been performed in an effort to better understand the formation of, and to develop strategies to mitigate, brittle punching shear failures in RC flat slabs. Of particular relevance to the subject of this paper, several investigations aimed toward studying the performance of RC members constructed with inclined shear reinforcement and illustrating the importance of adequate reinforcement anchorage in providing effective through-thickness shear reinforcement have been reported in literature.

Richart (1927) conducted a series of testing programs comprised of 139 RC beams with different web reinforcement arrangements, which were tested over a period from 1910 to 1922. Amongst the many findings reported from this work, it was shown that web reinforcement anchorage conditions played a critical role on the response of RC beams under shear loading conditions. It was noted that preventing the slipping of stirrups at their ends, by way of welding or other means, was a key parameter to the effectiveness of this reinforcement. Richart suggested that properly designed anchors and/or end-hooks seemed to be a reasonable method of improving the effectiveness of through-thickness shear reinforcement. Also of interest, it was specifically noted that inclined stirrups used as shear reinforcement in RC developed appreciable stresses under relatively low load levels in comparison to shear reinforcement stresses developed in beams constructed with vertically oriented reinforcing bars. Lastly, it was shown that RC beams reinforced with inclined shear reinforcement were capable of achieving shear capacities similar to those obtained by RC beams employing vertically oriented reinforcing bars with a reduced longitudinal spacing.

Oliveira et al. (2000) carried out an experimental program aimed toward investigating the efficiency of an inclined stirrup system. Eleven RC slabs, constructed at 1/2 to 2/3 scale, were tested. Two slabs were constructed without shear reinforcement, three contained conventional vertical stirrups that were orthogonally placed from the column faces, and five slabs were constructed with inclined through-thickness reinforcing members, with inclination angles of 57 degrees from the longitudinal axis. Results from the investigation showed distinctly better performance for the slabs containing inclined stirrups relative to those constructed with vertical stirrups. The authors suggested that the use of inclined stirrups was an effective way to increase the shear capacity of RC flat plates. Lastly, it was also noted that this particular shear reinforcement system permitted simple installation, allowing the inclined shear reinforcing members to be placed before or after all longitudinal reinforcement had been positioned.

Beutel and Hegger (2002) performed an experimental program consisting of ten RC slab punching tests with conventional stirrups and stirrups made of fabric reinforcement. In addition to the experimental work, three-dimensional finite element simulations were performed to investigate the effectiveness of different anchor types. Both the experimental program and the numerical simulations showed that the stirrup anchor details strongly influenced the effectiveness of the shear reinforcement. The maximum stirrup stress was obtained using a 180-degree bend that enclosed an orthogonal longitudinal reinforcing bar. The use of transverse welded bars was also shown to significantly improve the anchorage quality.

Muttoni et al. (2010) carried-out a study involving the use of inclined post-installed shear reinforcement as a means of strengthening flat plate RC slab-column connections. The retrofit solution involved the use of a series of steel bars, doweled and bonded within an existing RC slab using high-performance epoxy adhesive. The inclined reinforcing bars were installed in drilled holes into the soffit of the slab-column connection. Results from the testing program showed that the addition of the inclined shear reinforcing members in the slab-column connections led to significant increases in both strength and deformation capacity relative to that of slabs without shear reinforcement. Note that, in this case, the use of inclined bars was specifically selected as it led to increased anchorage lengths of the epoxy-bonded reinforcing bars. In the same study, the authors also noted that the capacity and rotation of the specimens was strongly influenced by the amount of shear reinforcement and the longitudinal reinforcement ratio.

RESEARCH SIGNIFICANCE AND OBJECTIVES

RC flat slabs containing inclined shear reinforcing members have been shown to outperform slabs containing vertically oriented through-thickness reinforcement in terms of both strength and deformation capacity. In some studies, this improved performance has been attributed to an increase in anchorage length (as compared to vertically-oriented through-thickness reinforcement). However, inclined shear reinforcement also has the potential to better engage shear cracks, reduce shear crack widths/improve crack distribution, and to improve the diagonal compressive resistance of shear strengthened RC slabs.

This paper presents the findings from an experimental testing program involving a series of five large-scale RC slab-column connections constructed with different shear reinforcement systems and subjected to concentric shear loading conditions. The tests were aimed at determining the merits and limitations of a novel inclined shear reinforcement system designed for RC flat plates. The performance of two-way slab-column connections containing the inclined reinforcement system, in comparison to that obtained by conventionally reinforced slab-column specimens, is determined on the basis of relative damage development, load-deformation response, capacity, and controlling failure mechanisms. Lastly, slab shear strength estimates developed using several design and analysis procedures are compared with those measured experimentally and their adequacy is discussed.

EXPERIMENTAL PROGRAM

Slab-Column Connection Details

Five full-scale RC slab-column connections were tested under concentric punching shear loading conditions. With the exception of the different shear reinforcement systems/configurations employed, the specimens were identical in terms of geometry, and were very similar in terms of in-plane reinforcement composition and concrete material strength (refer to Table 1). The shear reinforcement comprising the specimens served as the primary testing variable: slab-column connections S1 and S2 were constructed with conventional vertically-oriented headed steel studs as shear reinforcement, S3 was constructed with an inclined shear reinforcement system employing equally spaced inclined bars (i.e., working members), S4 was constructed with an inclined shear reinforcement system employing a variable working member spacing, and slab-column connection S5 was constructed without any form of shear reinforcement and served as the control specimen.

Table 1 -- Test Matrix

Specimen	ρ_l %	ρ_v [a] %	α [b] degrees	Shear Reinforcement Type / Longitudinal Spacing [c]	$(A_v/s)\cdot(\sin\alpha+\cos\alpha)$ [d] in.^{2}/in. (mm^2/mm)
S1	1.59	0.40	90	(2) US No. 4 vertical studs / equally spaced at 4.0 in. (102 mm)	0.100 (2.54)
S2	1.39	0.40	90	(2) US No. 4 vertical studs / equally spaced at 4.0 in. (102 mm)	0.100 (2.54)
S3	1.49	0.33	35	(4) 35°-inclined, US No. 3 bars / equally spaced at 7.5 in (191 mm)	0.082 (2.07)
S4	1.49	0.50	35	(4) 35°-inclined, US No. 3 bars / variably spaced from 5.0 in (127 mm) to 10.0 in. (254 mm)	from 0.123 (3.11) to 0.061 (1.56)
S5	1.39	-	-	-	-

[a] shear reinforcement ratio pertaining to critical section located d/2 from face of column (perimeter b_o = 97.5 in. (2477 mm))
[b] inclination of shear reinforcement (angle measured from slab longitudinal axis)
[c] shear reinforcement provided per column face
[d] A_v = area of shear reinforcement per column face; s = longitudinal spacing of shear reinforcement

The slabs comprising the connection specimens were 12-ft. (3.5-m) square, 10-in. (254-mm) thick, and were constructed with 16-in. (406-mm) square intersecting columns. The slabs contained two mats of in-plane reinforcing bars providing reinforcement ratios that ranged from 1.39 to 1.59 percent on the tension side and 0.22 percent on the compression side. In all cases, longitudinal tensile reinforcement consisted of US No. 7 ASTM A-615 compliant reinforcing bars and the longitudinal compression reinforcement consisted of US No. 3 ASTM A-615 compliant reinforcing bars. A clear cover of 0.75 in. (19 mm) was provided for the slabs and 1.50-in. (39 mm) cover was provided for the intersecting columns. The average depth to the centroid of tensile mat of steel was 8.38 in. (213 mm). The columns were constructed with longitudinal reinforcement ratios of 1.9 percent. All of the slab-column assemblies were designed such that punching shear failures would occur prior to the onset of yielding of the flexural reinforcement. Figure 1 provides an illustration of the typical geometry reinforcement details provided for the slab-column connection specimens.

The designs of the shear-reinforced slab assemblies were done according to the provisions of ACI 318-14. As shown in Figure 2, specimens S1, S2, and S3 were designed such that equal slab shear resistance was provided by the shear reinforcement (i.e., equal V_s according to the provision of ACI 318-14). However, S4, was designed such that it contained the same total volume of shear reinforcement, but was proportioned using a variable working member longitudinal spacing. This was done in an effort to maximize the shear resistance provided by the inclined reinforcing assembly near the column, where the shear stresses are greatest and punching failures are expected to occur. The nominal yield strength of the smooth studs was 63 ksi (435 MPa), whereas the nominal yield strength of the No. 3 deformed bars was 78 ksi (536 MPa). Figure 2 also presents the shear reinforcement area per unit length for each slab, as calculated and shown above in Table 1.

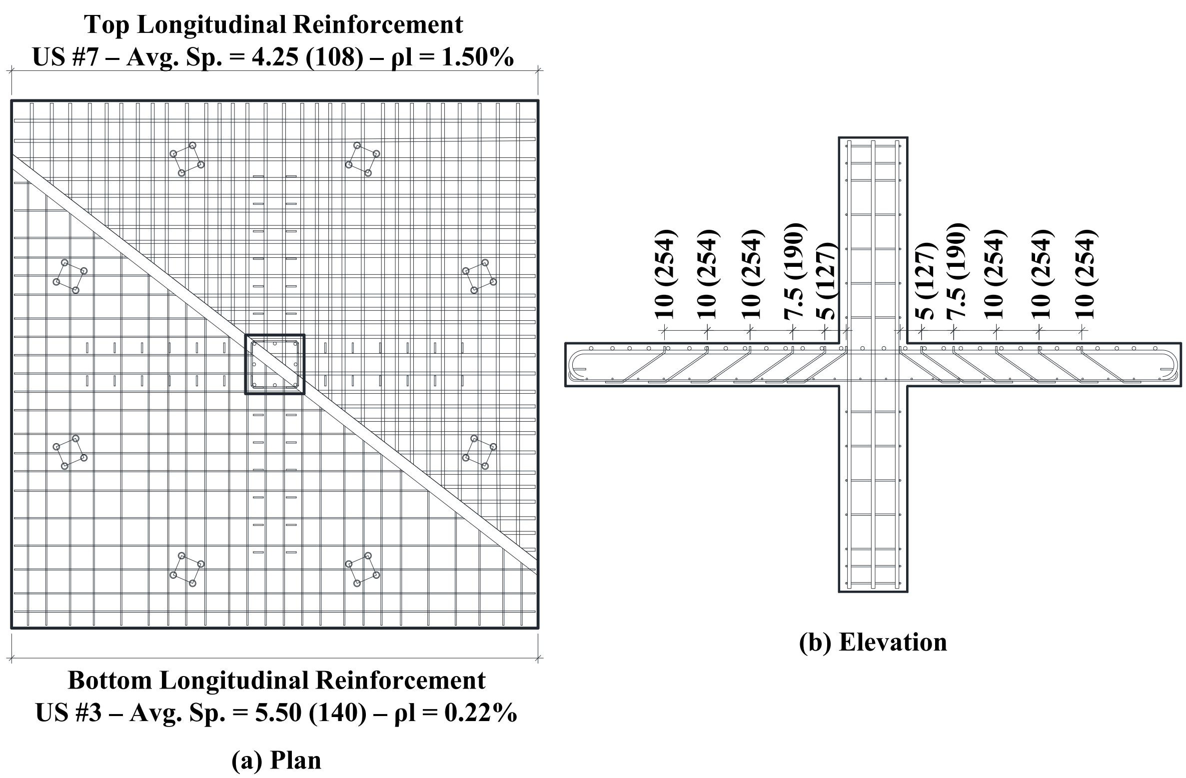

Figure 1 -- Specimen Reinforcement Details and Geometry (S4) [in. (mm)]

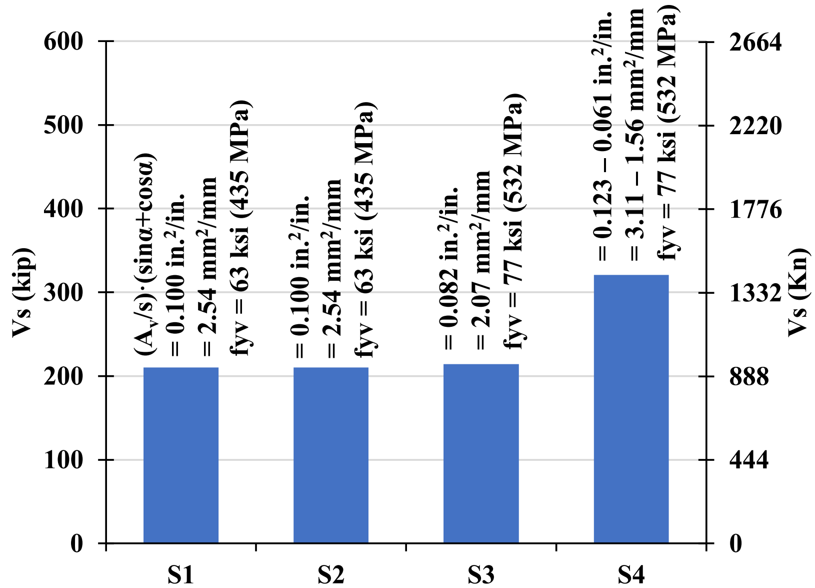

Figure 2 -- Shear Resistance Provided by Shear Reinforcement According to the Provisions of ACI 318-14

Details of the Inclined Shear Reinforcing Assembly

The inclined shear reinforcing system was made-up of an assembly of bent US No. 3 weldable (ASTM A706) reinforcing bars. The bent bars were welded in a stirrup-like configuration, which were anchored at the base of the slab (compression side) by way of steel horizontal runners. The working members of the system were bent with an inclination of 35 degrees measured from the horizontal plane. The top portions of the inclined members were bent back to vertical and with a 180-degree hooked configuration for the purposes of providing anchorage and limiting interference with the in-plane bars comprising the tensile mat of reinforcement (refer to Figure 3). The width of the assembly at the location of the runners was fabricated larger than the top (i.e., at the location of the 180-degree hook), which introduced a minor bend with an inclination on the order of 3 to 5 degrees, which permitted the fabricated assemblies to be stacked. A drawing of the inclined working members making-up the inclined shear reinforcing assembly is presented in Figure 4.

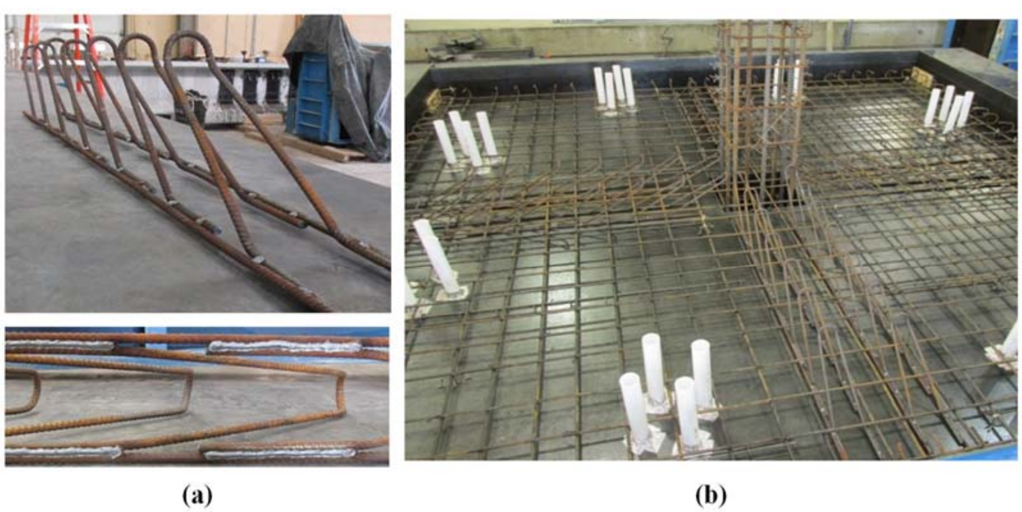

Figure 3 -- Inclined Shear Reinforcing System; (a) assembly, (b) as positioned in S3

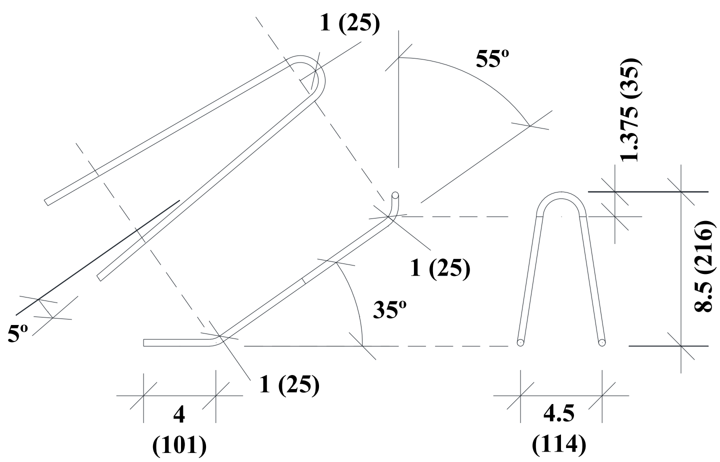

Figure 4 -- Inclined Working Member Geometry [in. (mm)]

Material Properties

Ready-mix concrete with nominal maximum-sized coarse aggregate of 1 in. (25.4 mm) crushed limestone, and a target cylindrical compressive strength of 4.0 ksi (27.6 MPa) was used. The test-day concrete compressive strength, f'_c, the modulus of elasticity, E_c, and the split tensile strength, f_{ct}, were evaluated from the testing of 4 x 8 in. (100 x 200 mm) concrete cylinders. The direct tensile strength of the concrete, f'_t, was determined from testing 'dog-bone' shaped concrete prisms with a 4 x 4 in. (100 x 100 mm) square cross section comprising the cracking region, under uniaxial tension. Lastly, standard rectangular prims with 6 x 6 in. (150 x 150 mm) cross sections loaded under four-point bending were used to evaluate the modulus of rupture, f_r. Table 2 presents a summary of results from the mechanical property tests performed, and also notes the ages of specimens at the time of slab testing.

Grade 60 steel reinforcing bars were used in the construction of the slab-column connections. The mechanical properties obtained from coupon testing of the steel reinforcing bars are presented in Table 3.

Table 2 -- Concrete Mechanical Properties

Slab	Age, Days	f'_c [a] psi (MPa)	E_c ksi (MPa)	ε'_c x 10^{-3}	f'_t psi (MPa)	f_r [b] psi (MPa)	f_{ct} [c] psi (MPa)
S1	107	4,180 (28.8)	4,890 (33,720)	-1.706	416 (2.87)	644 (4.44)	447 (3.08)
S2	65	3,100 (21.4)	4,840 (33,380)	-1.865	336 (2.32)	656 (4.52)	408 (2.82)
S3	38	4,190 (28.9)	3,720 (25,650)	-1.522	370 (2.55)	715 (4.93)	453 (3.12)
S4	25	3,900 (26.9)	3,450 (23,790)	-1.896	403 (2.78)	606 (4.18)	340 (2.34)
S5	33	3,260 (22.5)	3,220 (22,200)	-1.578	309 (2.13)	606 (4.18)	389 (2.68)

[a] Compressive Strength Test (ASTM C39)
[b] Modulus of Rupture Test (ASTM C78)
[c] Split Tension Test (ASTM C496)

Table 3 -- Mechanical Properties of Steel Reinforcing Bars

Type of Reinforcement	Designation	f_y ksi (MPa)	E_s ksi (MPa)	f_u ksi (MPa)
Longitudinal Compression	No.3	77.0 (531)	28,610 (197,300)	120.1 (828)
Longitudinal Tension	No.7	73.5 (507)	27,580 (190,200)	107.1 (738)
Shear Studs	½" headed	63.1 (435)	30,710 (211,700)	77.6 (535)
Inclined Shear Reinforcement	No.3	77.1 (532)	29,340 (202,300)	98.4 (678)

Details of Test Setup and Testing Procedure:

A vertical monotonically increasing load was applied to the lower column to produce concentric shear loading conditions in the slabs. Eight pin-pin connected vertical struts were positioned along the perimeter of the slab to serve as restraints. The struts were positioned in a circular restraint pattern with a diameter of 61 in. (1,500 mm), resulting in an average a/h ratio (shear span-to-slab height ratio measured from the center of the column) of approximately 5. The circular restraint pattern provided equal support-to-column shear spans amongst the struts. To ensure that the specimens remained stable, a lateral support-frame was also provided. Figure 5, Figure 6, and Figure 7 present additional details pertaining to the test setup.

Figure 5 -- Overview of Slab Testing Frame

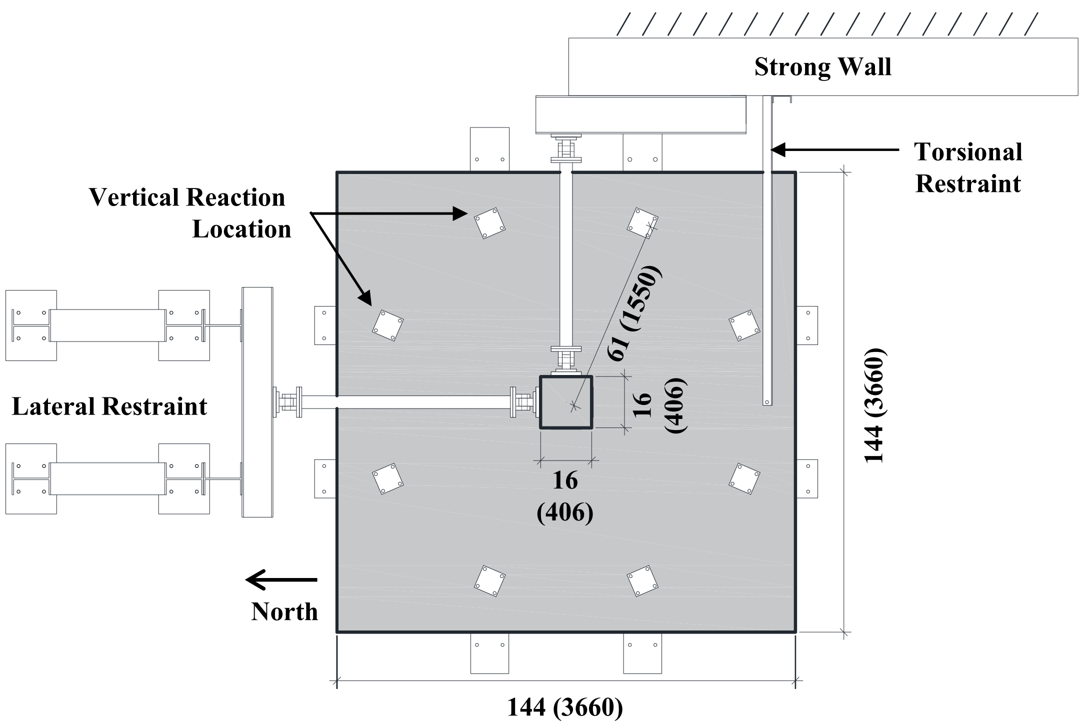

Figure 6 -- Test Setup Details - Plan view [in. (mm)]