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IN-PLANE DIAPHRAGM ISSUES FOR STEEL BUILDINGS IN SEISMIC ZONES

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Abstract

This paper summarizes issues related to the in-plane design of floor diaphragms in multistory steel buildings subject to earthquake shaking and describes areas requiring special consideration in design and for further research. It is shown that there is currently no accepted method to estimate the global likely demands on floor diaphragms appropriate for use in design, but the strengths and weaknesses of different approaches are summarized. The methods by which in-plane forces enter diaphragms; (i) inertia forces, (ii) transfer forces, (iii) slab bearing, (iv) compatibility and (v) interaction with other elements, are described. Methods available to transfer force within the diaphragm and to the beams and supports are discussed, and it is shown how the strut-and-tie method may be applied at the beam centres to obtain shear stud and beam axial forces. Finally, it is shown that if all slab forces are assumed to be resisted in a limited number of bays, special consideration is required for the location of shear connectors and tie reinforcement.

Keywords: Diaphragm; Steel Structures; In-plane forces; Diaphragm rigidity

1. Introduction

Significant advances have been made over recent years in the design of vertical lateral force resisting (VLFR) systems such as frames and walls in buildings subject to earthquake excitation. However, the in-plane seismic performance of floor diaphragms, and connections of such diaphragms to the VLFR elements has received relatively little attention. This is in spite of the fact that their integrity is essential for good frame performance. This was shown in the recent February 2011 Canterbury earthquake, where several buildings exhibited diaphragm distress and damage. In particular, one building, the CTV collapsed killing some 115 persons, and the diaphragm connection to the lift shaft/stair core was considered to be one of the contributing causes (Canterbury Earthquakes Royal Commission, 2012) [1].

Standards do consider diaphragm in-plane stiffness, and generally categorize diaphragms as either ‘rigid’ or ‘flexible’ for subsequent analysis. The majority in multistorey buildings are characterized as having rigid diaphragms. While standards require load paths to be followed, specific efforts to accomplish this are not always undertaken. This is because (i) reasonable methods to do this are still under development and are largely not incorporated in standards, and (ii) commonly used building design software often has a rigid diaphragm option and does not easily allow the diaphragm load paths to be followed.

Building diaphragms have traditionally been heavy but more recently, cold formed steel decking had has been used to support a thin concrete topping. This is often economical as there is no need for other formwork, there is a high construction speed, and the light weight reduces the sizes of other frame elements and foundations. Composite diaphragms existed in a small number of Christchurch buildings that experienced the 2010/2011 earthquake series. There was no obvious evidence of poor performance but this may be a result of good luck rather than good management.

For the reasons listed above it may be seen that it is necessary to understand diaphragm in-plane behavior so that guidelines can be developed which will ensure robust and desirable diaphragm performance during strong earthquake shaking.

This paper seeks to progress the understanding of diaphragm behavior to obtain strong diaphragms. As part of this, answers are sought to the following questions:

1) What floor diaphragm in-plane issues have not been fully addressed?
2) How can seismic demands on diaphragms be obtained?
3) What are the mechanisms by which in-plane forces enter the diaphragms?
4) How can diaphragm internal forces be evaluated?
5) How are diaphragm forces transferred to the frame?

2. Floor Diaphragm Issues

2.1 Rigid diaphragm assumption

Diaphragms’ in-plane stiffness can be very high, very low, or in-between. For simplicity, many standards consider that a diaphragm can be treated as being either fully rigid or flexible. Most diaphragms in multi-storey buildings are assumed to be rigid and are generally analyzed elastically with software that makes the rigid-diaphragm assumption. Such software commonly does not make it easy for designers to consider how load paths should be followed, so separate analyses are required to find the likely forces within the diaphragm and the beam axial forces. Furthermore, there is currently no accepted consensus about the best way to do this analysis, and various methods have only recently been proposed.

Overestimating diaphragm stiffness may also have consequences such as (i) structural periods may be underestimated and can result in both higher accelerations and displacements. Colunga and Abrams (1996) [2] state that the rigid-diaphragm assumption is not necessarily conservative for flexible-diaphragm systems and may result in incorrect estimation of earthquake loading for whole structure. (ii) The building torsional effects may be overestimated (Colunga and Abrams, 1996) [2]. (iii) The demands on gravity frames are underestimated, as shown in Fig. 1 where a gravity frame may exist at the location of highest drift. This may lead to non-ductile diaphragm failure or structural instability due to high drift demands in the gravity system (Fleischman et al. 2002)[3]. The consequences of gravity system failure due to high drift demands can be severe as evidenced during the Northridge earthquake by collapsing several parking structures (EERI, 1994)[4]. (iv) the demands on other components that are not designated as being part of the seismic force-resistance system, such as slab-column and slab-wall connections, and cladding attachments may be underestimated (Moehle et al. 2010)[5].

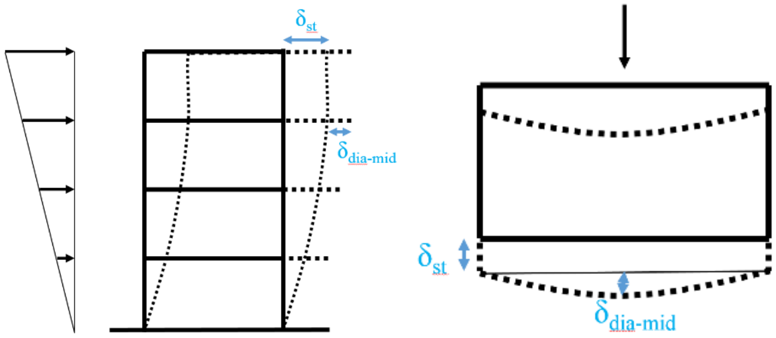


Fig. 1- Diaphragm flexibility effect (Fleischman et al. 2002) [3]

2.2 Neglecting the beam axial force in connection design and beam capacity

Beams in moment-frames are often considered to carry bending only and it is often assumed that the slab will transfer the lateral forces to the column through compression on the column face. However, since slab inertia forces act in the same direction as the frame sways, a gap opens at location “A” shown in Figure 2. Because of this, slab inertia forces cannot go directly into the column. Instead, the forces must move into the steel beam through friction and mechanical transfer using studs (MacRae and Clifton, 2015) [6]. This situation imposes axial forces to beam plastic hinge regions and connections at the beam ends that should be considered in design procedure. Also, if there is no construction gap between the slab and column, as the column sways, it bears against the concrete slab on the far side of the column causing a slab-interaction effect that increases the forces that the slab must transfer into the beam, and which the beam must transfer back to the columns. Axial forces in beams may decrease the structures’ lateral strength and deformation capacity.

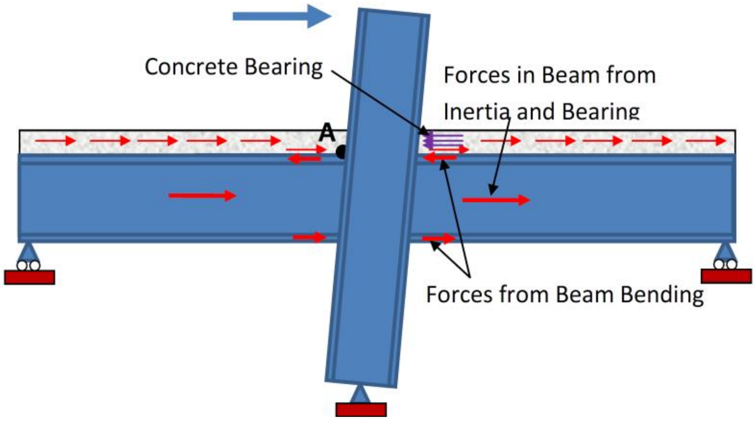


Fig. 2-Beam axial force (MacRae and Clifton, 2015) [6]

2.3 Acceptable floor slab thickness

Floor diaphragm thickness is sometimes based on fire insulation, acoustic insulation or in-service vibration considerations. SDI [7] and NZS 3101 2006[8] both require that the minimum concrete thickness on top of the steel deck shall not be less than 50 mm. The background to this dimension is not clear, but it is not based on buckling considerations. The topping thickness is above the top of the steel decking, rather than about the depth of the trough, as some decking types have a significant cap above the main trough depth. It is possible that out-of-plane global, or local, buckling due to slab in-plane forces (together with any initial out-of-plane forces/deformations) has not been explicitly considered in design. These buckling and related crushing modes may limit the ability of the slab to reliably carry diaphragm in-plane transfer forces during earthquake shaking (Fig. 3).

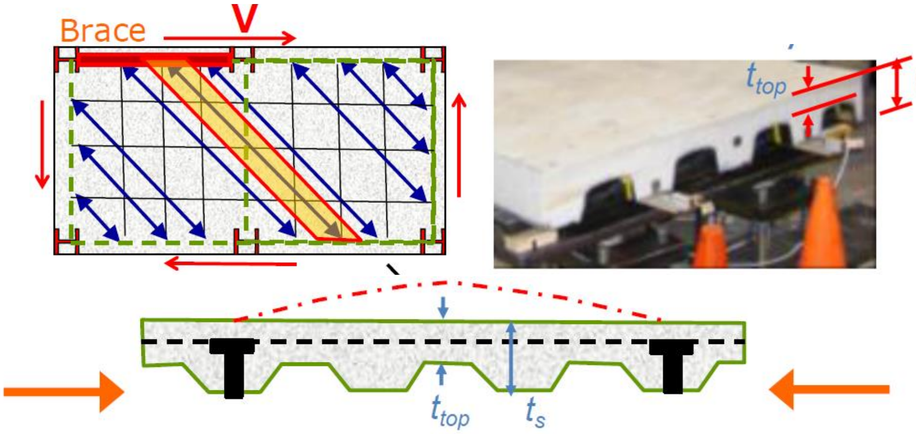


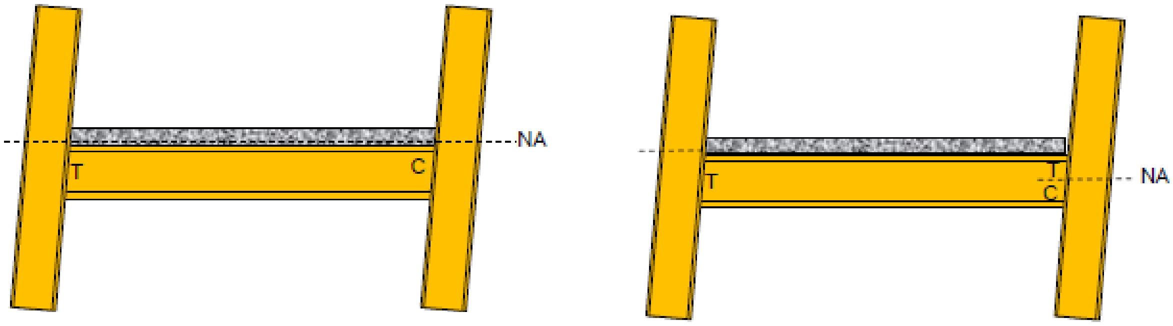
Fig. 3- Buckling of diaphragm due to large imposed forces (MacRae and Bull, 2015) [9]

2.4 Elongation issue in composite beam elements

During earthquake events, “beam growth” occurs in reinforced and pre-stressed concrete structures due to cyclic loading. This is because concrete structures carry the load well in compression, but tend to crack/gap in tension. It causes damage the slab and it can push columns apart causing additional demands on the structural frame.

In steel structures, when the slab is not strong in tension, then the neutral axes at the different ends of the beam are at different heights as shown in Figure 4b. The neutral axis due to flexure is on the right-hand side is through the center of the beam, while that on the left-hand side of the beam may be in the slab. This would imply more tension yielding at the center of the beam than compression yielding and some net elongation. This elongation would be expected to be much less than that of a concrete beam where cracks/gaps open at both ends of the beam (MacRae et al. 2013) [10].

Beam elongation measurements by MacRae et al. 2013 [10] on some slab-beam-column subassemblies showed that the residual shortening, measured as the shortening at zero column drift, was less than 2mm during cycles up to about 3.5% drifts. This would probably not be significant in a typical structural beam, but subassemblies showing gap opening characteristics such as those with reinforced concrete beams, can place much greater demands on the diaphragm (SESOC 2011) [11].



(a) Strong Slab around Column (b) Weak Slab Around Column

Fig. 4-Deformation of Steel Beam with Different Strength Slabs (MacRae et al. 2013) [10]

2.5 Load path concept in diaphragms

Although the load path concept is emphasized in undergraduate structural classes around the world, it is not generally considered in diaphragm design. One reason may be that there is currently no generally accepted procedure for evaluating diaphragm forces during earthquake event as discussed in Section 3.

In addition, even if the diaphragm-imposed forces are evaluated realistically, an appropriate method is needed to analyze the floor diaphragm in a rational and suitable manner for a design office. Several methods have been proposed by researchers in this regard. These are mostly for pre-cast and cast in-situ concrete floors and they might need some modification for diaphragms using cold formed decking.

2.6 Slab Effects on Subassembly Strength and Degradation

Floor slabs generally sit on steel beams. Generally, shear studs are provided to make a steel-concrete composite member, which is considered to have greater strength and stiffness than the steel beam alone under gravity loads. Also, in the case of lateral loading, the beam is generally considered to have an increase in stiffness and strength along its length as a result of composite action. However, the current NZ design approach (NZS 3404, 2009) [12] states that under lateral seismic loading:

i) The strength at the end of the beam should be that due to the non-composite steel beam alone. This is because the effect of the slab is not considered to be reliable.

ii) For determining the beam overstrength effects to compute column demands, the slab effect be explicitly considered (if the slab is in contact with the column) and methods to do this are specified. This overstrength requirement is unique to NZS 3404 (2009).

3. Methods to Estimate Diaphragm Forces

In order to conduct an analysis of floor diaphragms, the global force demands affecting the diaphragms are required. Procedures for estimating floor diaphragm imposed forces for design must be: (i) Simple enough to be used in design offices, (ii) Compatible with the commonly used elastic 3D software, and (iii) Indicate likely magnitude of demands (MacRae & Bull, 2015 [9], MacRae & Clifton 2015 [13]).

The following methods are available for estimating floor diaphragm imposed forces: (i) Full 3D Non-linear Time History Analysis (NTH), (ii) Method proposed by Sabelli et al. 2011 [14], (iii) Equivalent Static Analysis (ESA) and Overstrength ESA (ΦESA), (iv) pseudo Equivalent Static Analysis (pESA), (v) Parts and Components method (P&C) and (vi) a method that combines inertial forces, compatibility forces and transfer diaphragm forces [15].

These methods range from advanced methods like the use of nonlinear time history analysis to simple methods like ESA. Amongst the simple methods that are used with elastic frame analysis, there is no correct method for estimation of diaphragm in-plane demands. It is noted that, transfer, bearing and continuity forces can cause significantly larger forces than that from inertial considerations alone.

Section 4 presents the types of structural system actions that can generate in-plane diaphragm forces.

4. Slab In-Plane Demands

Specific types of structural system actions that can generate in-plane forces in diaphragms are considered below.

4.1 Inertia forces

In steel frame structures, concrete diaphragms comprise a significant portion of the building mass. Therefore higher inertia forces may be imposed to the floor diaphragm and consequently to the connections between diaphragm and the steel frame. Diaphragms are expected to remain elastic, or almost so, during seismic shaking, while other elements are expected to dissipate the seismic energy.

Inertia forces of floor slabs are often considered to be transferred to the steel frame through compression of the slab on the column face. However, as was shown in Fig. 2, since slab inertia forces act in the same direction as the frame sways, a gap opens at location “A”. Therefore, slab inertia forces cannot go directly into the column. Instead, the forces must move into the steel beam through friction and mechanical transfer using shear studs, along the beam causing axial force, through the beam, the plastic hinge and connection into the column (MacRae and Clifton, 2015)[13].

4.2 Transfer forces

Transfer forces are diaphragm shear forces, which occur as a result of deformation incompatibility of different vertical lateral force resisting (VLFR) elements such as moment frames and RC walls wanting to move different amounts at different levels under the applied loading. The classic illustration of transfer forces is shown in Figure 5 (Paulay and Priestley, 1992 [16]). Here the wall and frame want to move together at the base, and apart near the top. This causes compression and tension in the links between these two VLFR systems. These links represent the diaphragms, which must carry these forces as in-plane diaphragm transfer forces. The magnitude of diaphragm transfer forces may be significantly increased where there are discontinuities in the VLFR elements. A common discontinuity in the vertical elements is at a podium slab.

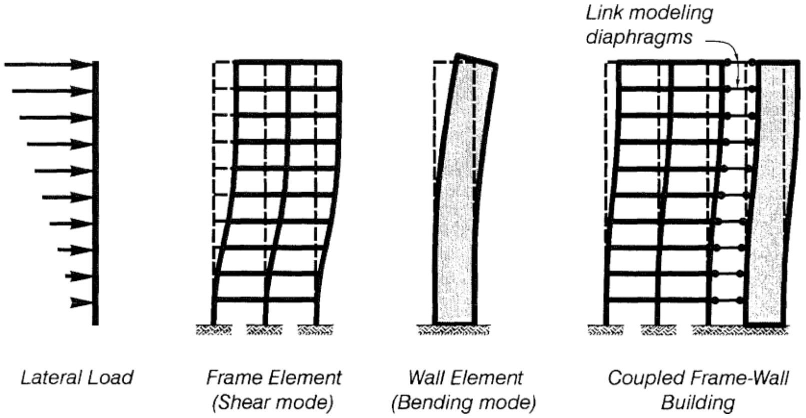


Fig. 5- Transfer forces due to deformation incompatibility (Paulay and Priestley, 1992) [16]

While transfer forces are generally illustrated as being an issue for multistory structures, they can also affect single storey structures. The magnitude of transfer force depends on the strength and stiffness of the VLFR elements and does not necessarily occur at the peak floor displacement.

4.3 Slab bearing forces

If there is no construction gap between the slab and column, then as the column sways, it bears against the concrete slab on the far side of the column from point “A” in Figure 2 (MacRae and Clifton, 2015)[13]. This causing an extra bearing forces on the slab. This force must be transferred through the slab, shear studs, beam, and back to the column.

The magnitude of slab bearing forces is a function of concrete compressive strength, number and strength of shear studs, and force transferring mechanisms into column. Force limiting mechanisms depend on parameters such as flange yielding, shear key type beam/connection strength, and concrete confinement as discussed by Chaudhari et al. 2015 [17] and MacRae and Bull, 2015 [9]. If confinement of the top surface of the concrete slab is not provided beside the column, strength of the slab due to bearing is not sustained through large deformations so it can spall. Other mechanisms of slab strength loss, such as shear key fracture, and longitudinal splitting, can also occur (Chaudhari et al. 2015, MacRae et al. 2013 [10] and Hobbs et al. 2013 [18]).

Disadvantages of allowing the concrete slab to bear against the column include the following: (i) bearing of the column against the concrete increases the beam moment input into the column, $M_{p,beam}$. This is typically 30% and it requires larger column sizes (MacRae and Bull, 2015) [9]. (ii) Since it is difficult to confine the concrete slab properly, after spalling of the concrete occurs, the composite beam strength degrades to $M_{p,barebeam}$ and causing loss of strength as shown in Fig 6 (MacRae et al. 2013)[10]. (iii) Once spalling of the concrete occurs in one direction, the strength of the subassembly in the different directions are different increasing the likelihood of ratchetting deformations in one direction only (MacRae and Bull, 2015) [9]. (iv) The composite action increases the beam axial forces, which act through connection and beam plastic hinge (MacRae and Bull, 2015) [9]. Some beam growth effects are also possible.

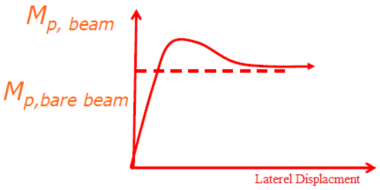


Fig 6. $M_{p,beam}$ composite degrades to $M_{p,bare}$ beam due to lack of confinement (Chaudhari et al. 2015) [17]

In order to avoid these effects there have been efforts to more economically design frames with slabs. These include (i) designing the slab around the column to limit strength degradation during large deformations by special detailing around the column (MacRae et al. 2013[10] and Chaudhari et al. 2015[17]), and (ii) providing a gap between the column and the slab to avoid bearing effects as shown in Fig. 7.

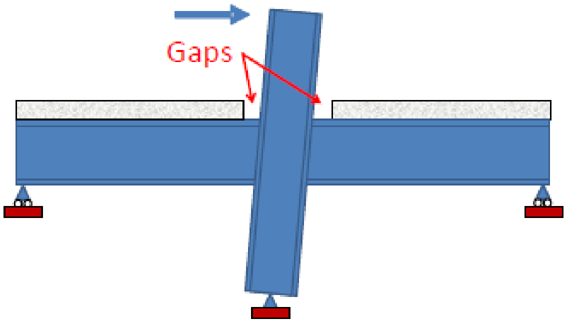
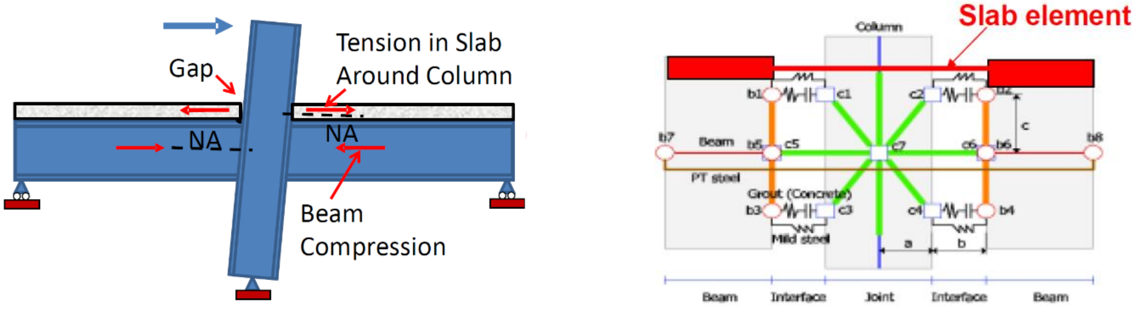


Fig. 7- Gap between the column and the slab (MacRae and Bull, 2015) [9]

4.4 Compatibility forces

When neutral axes of beams on either side of the column are at different heights due to composite action of slab as shown in Figure 8a, the distance between beam-ends wants to change, causing slab (tension) forces and beam (compression) forces (MacRae and Clifton, 2015)[13]. This elongation would be expected to be much less than that of a concrete beam where cracks/gaps open at both ends of the beam (MacRae et al. 2013)[10] but it should be taken into account in analysis because it can impose extra forces on column as well as on beam plastic hinge region and beam column connection. As shown in Fig. 8b, the slab effect on moment-resisting structural systems can be modelled (Umarani and MacRae, 2007[19] and Ahmed et al. 2013[20]), but it is not considered in most analyses.



a) Neutral axes of beams at different heights (MacRae and Bull, 2015) [9]

b) Slab effect modeling (Umarani and MacRae, 2007[19] and Ahmed et al. 2013[20])

Fig. 8- Composite action of slab

4.5 Forces due to Interaction with other elements

As the main role of diaphragms is tying structural elements together, they interact with these other elements. This interaction may impose various forces to the diaphragms. Inclined columns, as shown in Fig. 9, can develop diaphragm in-plane tension and compression forces due to gravity and overturning actions (Moehle et al. 2010 [5] and Scarry, 2014 [21]). These forces should be taken into account in diaphragm design.

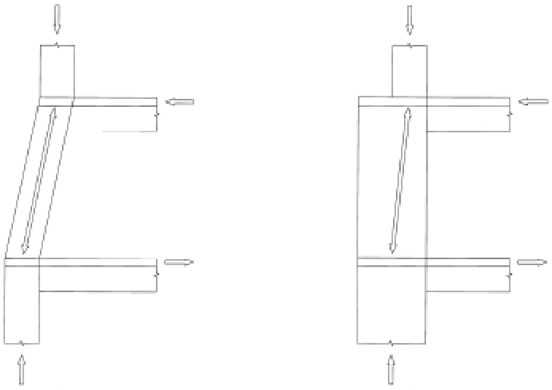


Fig. 9-Diaphragm forces due to sloped column (Scarry, 2014) [21]

Ramps and sloping diaphragms are another source of interaction forces. The effect of ramps can be more significant especially where they connect different stories of a structure and story shear can migrate out of the vertical elements of the seismic force-resisting system through the ramp in the form of shear or axial forces (Moehle et al. 2010)[5]. This effect should be considered in analyses and modeling the structure.

5. Slab Analysis

After evaluating the global diaphragm in-plane forces using methods of the type described in Section 3, separate analysis are required to specify the load paths and diaphragm internal forces for design purposes. The forces on the diaphragm are obtained from the difference in shear above and below each vertical element passing through the floor system. These, together with the applied forces at the diaphragm, result in a floor system that is in equilibrium, and the different components can be designed (MacRae and Clifton, 2015) [13]. Slab analysis methods include ‘Finite Element Method (FEM)’, ‘Deep Beam’, ‘Strut and Tie’ and ‘Truss method’. These methods vary in the level of complexity and accuracy.

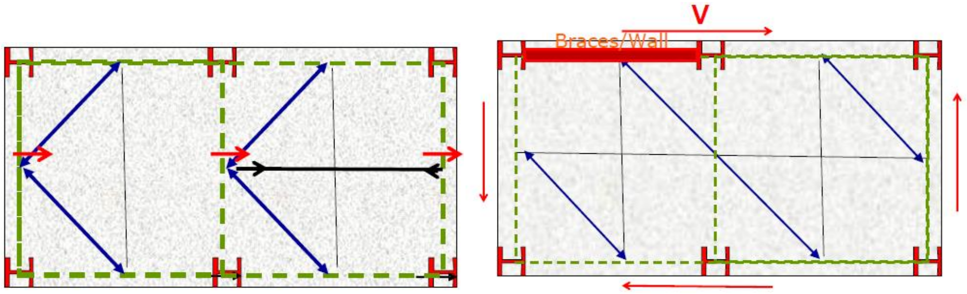
The finite element method is one of the most widely accepted numerical solutions for exploring engineering problems. Modeling a diaphragm using FEM can be beneficial for evaluating the transfer forces among vertical lateral load resistance elements and inertia forces, especially for irregular diaphragms in shape and around large openings in floor plan as well as the impact of ramps in parking garages (Moehle et al. 2010)[5].

In spite of its advantages, (i) performing a finite element analysis of a floor diaphragm can be very complicated in terms of modeling, (ii) the stresses and strains do not related directly to design and it may be difficult to estimate how much reinforcing bar is required, and (iii) FEM programs are often expensive, difficult to use and require significant process and post-processing times for each analysis (Scarry, 2014) [21].

An effective diaphragm analysis method is the ‘Strut and Tie’ approach (Bull, 1997 [22], Gardiner, 2011 [23], Bull, 2004 [24], Bull, 2014 [25] and Scarry, 2015 [26]). This method can be used easily for general floor plan layouts with different irregularities such as holes in the diaphragm. In the Strut and Tie method, compression struts and tension ties are placed throughout the floor slab to develop a truss system of admissible force paths (Gardiner, 2011) [23].

When strut-and-tie analysis is used, shear studs on the top of any beam can be represented by one effective stud at the center of the beam span (MacRae and Bull, 2015) [9]. Axial forces parallel to the beam are resisted by the beam, tension force demands perpendicular to the beam can be resisted by steel placed in the slab, and compression forces at different angles to the beam axis are resisted by the concrete. This approach also gives axial forces in the beams, which also must be considered in the design (MacRae and Clifton, 2015) [13].

The advantage of the Strut and Tie method is that it allows detailing of irregular floor geometries and more complex floor layouts (Gardiner, 2011 [23] and Bull, 2004 [24]). In addition, it provides information that are more useful for the designer than the deep beam method. Figure 10 shows the implementation of strut and tie in a simple diaphragm for inertial and transfer forces. This method also has the disadvantage that it cannot identify the slab compatibility forces (Scarry, 2014) [21].



a) Inertial forces b) Transfer forces

Fig. 10- Strut and tie solution in a typical diaphragm (MacRae and Bull, 2015) [9]

The truss method is a type of strut-and-tie analysis with compression-only pairs of diagonals representing the diagonal concrete struts throughout the diaphragm (Scarry, 2014) [21]. Here, multiple load cases can be analyzed by one model. Also, complex three-dimensional diaphragms can be modeled and the “a-priori” location of strut and tie lines is not needed.

In addition to the numerical studies described above, experimental testing is required to ensure that the methods used are reasonable. Currently there is a lack of such test results, and testing is urgently required.

6. Load transfer from diaphragm to frame

Many buildings have a limited number of seismic frames, which are designed to carry horizontal forces from the diaphragms to the foundation. Two options to transfer this horizontal force can be considered in design:

1) Designing diaphragms to transfer horizontal force out only through the seismic frame beams

In this case, forces on the diaphragm, including inertial and transfer forces, are transferred to the seismic beam via shear studs. On the gravity beams, horizontal shear transfer should be mitigated by placing no shear studs and a lubricant between the frames. The advantage of this method is that no horizontal force on the gravity beams is expected, so beam axial tension/compression does not need to be considered and a simple beam-column connection maybe appropriate.

2) Designing diaphragms to transfer horizontal force through beams outside the seismic frame.

When composite action of the gravity beams is desired, or when it is considered undesirable to minimize axial force going into the gravity beams, the beams and their connections need to be designed for the expected forces considering also drag strut action.

7. Conclusions

In-plane design considerations for floor diaphragms in steel buildings are described. It is shown that:

1) A number of issues that are not generally explicitly considered in current standards or current design, are described. These include: (a) diaphragm rigidity/flexibility considerations, (b) beam/connection axial forces, (c) thin diaphragm buckling, (d) elongation issues in composite beams, (d) load paths within a diaphragm to the supports, (e) likely modes by which diaphragms are exposed to in-plane forces, and (f) slab effects on subassembly strength and degradation.
2) A number of methods proposed to estimate forces on a building to estimate global diaphragm in-plane demands are described. These vary in complexity and rationality. While no one method has

been accepted as being appropriate for design using commonly available design software, it is beneficial to select one distribution of forces which can capture the likely inertial and transfer effects considering overstrength.

3) The following five types of diaphragm in-plane forces are discussed: (i) inertia forces, (ii) transfer forces, (iii) slab bearing, (iv) compatibility and (v) interaction with other elements may be considered in the global analysis. It is also shown that because of the way frames move, diaphragm inertial forces cannot generally to be transferred directly from the slab into the column, so appropriate consideration of the shear studs, and axial forces in the beam and connection are required. The inertia forces are affected by frame overstrength. Transfer forces are affected by the distributions of stiffness and strength not only over the building height, but also within one storey. Slab bearing and compatibility forces are affected by any gap provided between the concrete slab and column.
4) When strut and tie method is used to model the diaphragm for design it is proposed that nodes are placed at beam centers to allow beam axial demands to be captured.
5) Diaphragm in-plane forces can be transferred into the frame through shear studs on the gravity beams, on the seismic beams or both. The choice made affects the frame detailing. Strength should be provided to ensure the likely load paths.

8. Acknowledgment

This paper is based on the course presentation for the postgraduate course “Advanced Steel and Composite Structures” by MacRae and Bull (2015) [9] as well as on subsequent discussions. This is a shorten version of one submitted to NZSEE bulletin.

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