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DESIGN OF FLOOR SYSTEMS FOR SEISMIC FORCES

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This Technical Note outlines the procedure for design of floor systems that participate in resisting seismic forces as part of a building's primary force resisting path. It concludes that the design procedure depends on the method of arriving at seismic forces.

1 – BACKGROUND

In regions of low and moderate seismic activity, it is permissible to consider a building's floor slabs to participate as primary structural members in resisting the seismic forces. These are regions generally classified as subject to low or moderate seismic risk. International Building Code (IBC 2009) groups them as regions of Seismic Design Categories (SDC) A, B and C. Table 1-1 gives the associated classifications in other major building codes. The focus of this Technical Note is the design of floor systems in low and moderate seismic regions, such as UAE and Florida.

TABLE 1-1 CORRELATION AMONG THE SEISMIC RISK CLASSIFICATIONS OF MAJOR BUILDING CODES

Code /Standard Resource	**➢ Level of Seismic Risk** **➢ Assigned Seismic Performance** **➢ Code Defined Category**		
IBC 2009 ASCE 7-05 ACI 318-08	**SDC A,B,**	**SDC C**	**SDC D, E, F**
UBC 1997	**Zone 0,1**	**Zone 2**	**Zone 3,4**
Eurocode 8	**Very Low Seismicity**	**Low Seismicity**	**Seismically Active**
Other	**Low**	**Moderate**	**High**

The seismic design forces for a building are generally determined using either a (i) pseudo-static, or (ii) dynamic analysis. The most common dynamic analysis procedures ar
e the "response spectrum," and "time-history."

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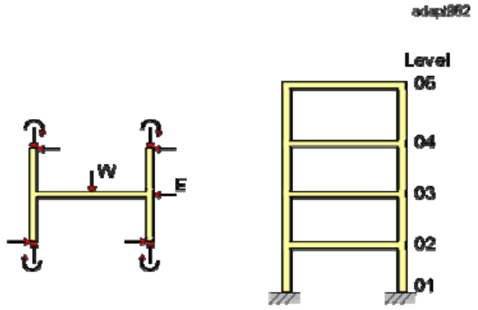
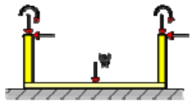
The common procedure for the design of elevated floor slabs, mat foundations, and transfer plates in low and moderate seismic regions is to (i) perform a lateral (stability) analysis of the entire multistory building; (ii) consider each of the floor slabs in isolation, (iii) extract the seismic forces at the connection of the designated lateral force resisting members to the selected floor; (iv) validate the extracted seismic forces for static equilibrium; (v) apply the extracted seismic force to the floor system and determine the resulting moments and shears in the floor; (vi) combine the calculated forces from the seismic effects in the floor system with those due to gravity; and finally (vii) design the floor system to resist the combined actions. The preceding steps will be described through the illustration in Fig. 1-1.



(a) Substructure of level 03 (b) Elevation of frame



(c) Substructure of level 03

FIGURE 1-1 VIEW OF MULTI-STORY BUILDING AND EXTRACTION OF A FLOOR FROM THE MULTISTORY.

Figure 1-1a shows level 3 of the multi-story frame extracted from the building for the purpose of designing its floor system. The forces shown at the far ends of the columns connected to this level are those obtained from a seismic analysis. The action of these forces on the isolated substructure shown in Fig. 1-1a will give the moment, shear and the axial force for which the floor has to be designed. A similar condition exists for mat foundations as illustrated in part (c) of the figure.

Figure 1-2 illustrates a floor slab in isolation under the action of seismic forces at the far end of the columns and walls attached to it. In the case of transfer slabs one or more of the seismic members from above terminate on the floor system, and others start from below the floor. In this case the entire actions from the planted members from above must be transferred through the floor to its supports.

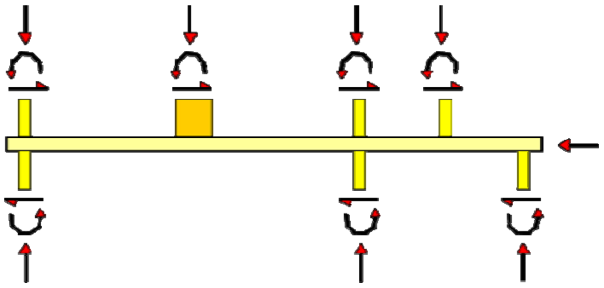
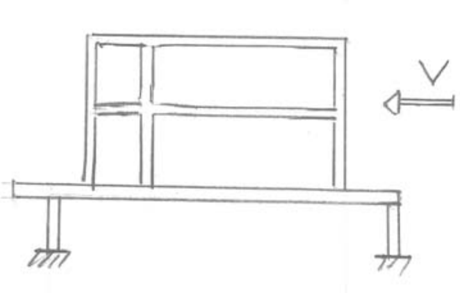


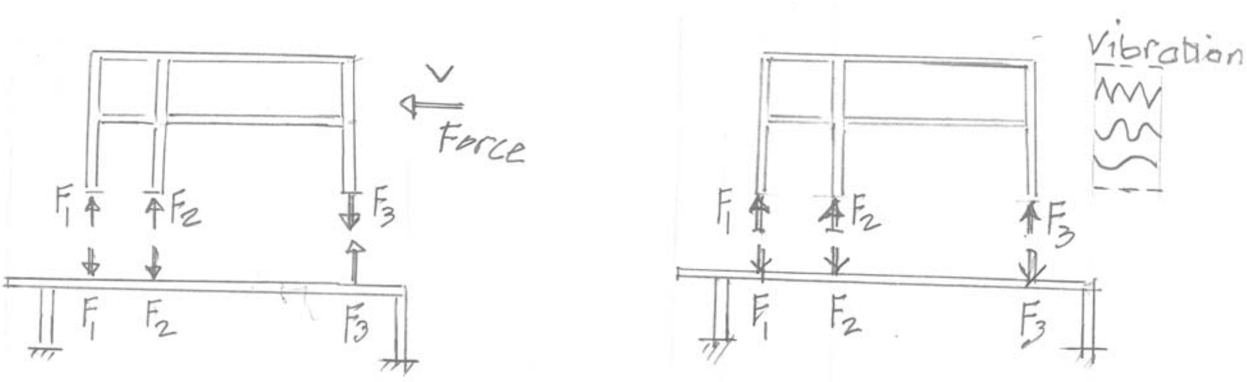
FIGURE 1-2 VIEW OF AN ISOLATED FLOOR AND THE ASSOCIATED LATERAL FORCES

2 – PSUEDO-STATIC VERSUS DYNAMIC ANALYSIS

The salient design features of the slab for forces obtained from either a pseudo-static or dynamic analysis are illustrated through the simple example of a transfer plate shown in Fig. 2-1.



FIGUE 2-1 VIEW OF A SEISMIC FRAME ON A TRANFER PLATE



(a) Forces from pseudo-static analysis
Note the direction of forces

(b) Forces from dynamic analysis
Note the direction of forces

(c) Distribution of moment from pseudo-static analysis

(d) Distribution of moment from dynamic analysis

FIGURE 2-2 SEISMIC AC4TIONS ON TRANSFER PLATE
(Note that forces from a static analysis are results of "an applied force," whereas those from a dynamic analysis are the "envelopes of dynamic excitations."

Pseudo-static analysis

The forces F1, F2 and F3 in Fig. 2-2a from the static analysis of the frame are the results of the seismic force V (base shear) distributed over the height of the building. For simplicity, without loss of concept only the vertical forces are shown (assuming hinge at connections). F1, F2 and F3 satisfy the static equilibrium with the applied force V. Simply, their total adds up to zero, and the sum of horizontal forces add up to V, and the moment due to these forces adds up to the overturning moment from V.

The response of the transfer floor to the seismic forces can be determined by analyzing the floor using the principles of solid body mechanics, similar to the procedure used for gravity forces. The outcome of the analysis for the example shown may include a moment distribution as shown in part (c) of the figure. This moment will be combined with moment from other forces acting on the floor to determine the required reinforcement.

Dynamic analysis

Unlike the static analysis where the solution is the outcome of application of a single set of applied forces (distributed base shear over the height of the building), the forces F1, F2 and F3 reported from a dynamic analysis are the results of a multitude of solutions, each of which referring to a specific frequency, mode shape or impulse. From the multitude of underlying solutions, the envelope of maximum values are selected, possibly scaled, are reported. Consequently, a force such as F1 in part (b) of the figure can be the maximum value from one frequency and F2 from a different frequency. Obviously, the envelope of forces extracted from a dynamic analysis will not be in static equilibrium. This is a general characteristic of actions generated through enveloping. Further, many commercially avaible software delete the sign of the design forces extracted from a dynamic analysis and report them all as positive or negative values due to the fact that (i) the seismic actions can act in any direction; and (ii) the force reported at one location does not have a bearing with either the force or sign of another force at a different location.

In summary, it is meaningless to apply a set of forces derived from a dynamic solution to a floor system with the objective to obtain a solution for the overall response of a floor system to seismic effects. Figures 2-2c and d are intended to illustrate the differences symbolically.

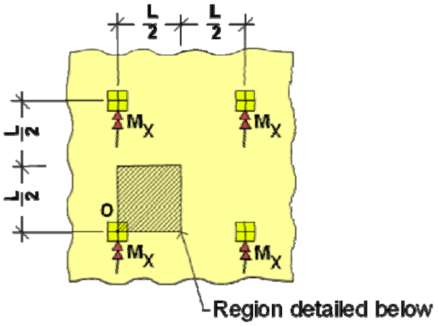
The forces reported from a dynamic analysis, however, serve the purpose for which they are generated, since these forces are used to determine the reinforcement in the members of the superstructure. In designing the structural members of a superstructure, each member in general is viewed in isolation and designed for the maximum demand from a seismic event. In most cases, the values are used to determine the reinforcement at “sections” as opposed to “members.” When dealing with a floor system, and looking for the response of the “entire” floor to seismic actions, the seismic forces to be applied to the floor system should be consistent. For design of a floor system subjected to actions from a dynamic seismic analysis an alternative approach, such as the one outlined in the following may be adopted.

3 - LOCAL RESPONSE OF A FLOOR SLAB TO SEISMIC FORCES

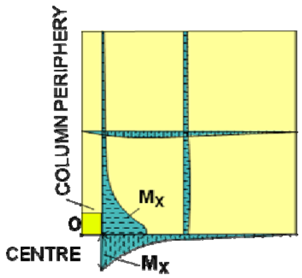
Before dealing with a design procedure for actions extracted from dynamic procedures, it is necessary to review the response of a slab localized seismic actions.

3.1 Distribution of Seismic Moment in Slab

Figure 3-1 shows the distribution of column moment in a typical slab panel. Observe that (i) the maximum value is at the face of the column and (ii) the moment disperses rapidly into the slab and drops in magnitude to zero at midspan for regular support layout.



(a) Typical interior panel



(b) Moment dispersion shown in quarter slab

FIGURE 3-1 DISTRIBUTON OF COLUMN MOMENT IS SLAB

The above observation leads to the conclusion that the likely critical location is the “design section” at the face of column. A safe solution can be obtained by: (i) finding the value of moment at the face of the column, (ii) combining the moment with those of other load cases, (iii) determining the added reinforcement due to the load combination that includes the seismic contribution, and (iv) distributing the reinforcement over and on each side of the column within an “effective” width, and (v) extending the length of the added reinforcement from seismic effects over an appropriate length.

3.2 Magnitude of Seismic Moment in Slab

A moment from a column/wall transfers to a slab by way of three components, namely (i) a moment in front of the column\/wall connection; (ii) a moment on the opposite face of column/wall; and (iii) torsion of the slab strips attached on each side of the column/wall (Fig. 3.2-1) The larger the aspect ratio of the column/wall in direction normal to the axis of the moment (a/b), the greater is the contribution of torsion.

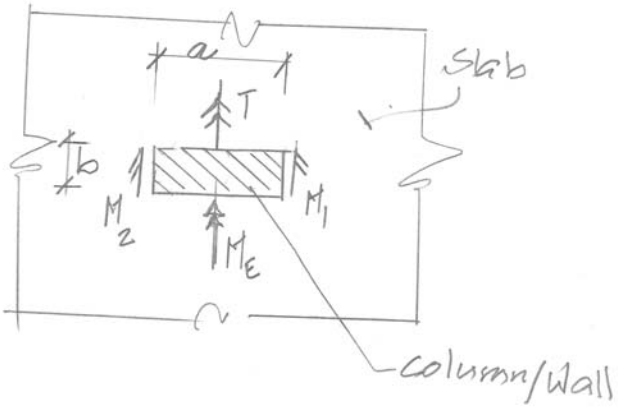
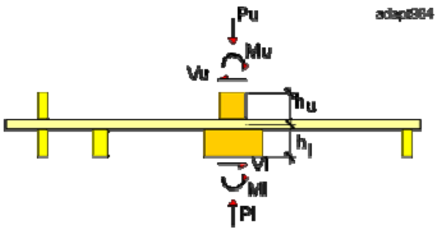
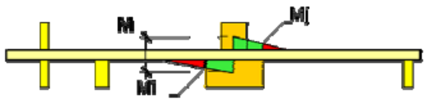


FIGURE 3.2-1 TRANSFER OF COLUMN/WALL MOMENT TO SLAB
(Applied moment M_E is resisted by moments M_1, M_2 and torsion T)

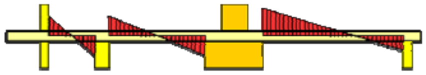
For orthogonally laid out and uniform column arrangements, the moments on the front and back faces of a column will be equal.



(a) Actions on a shear wall



(b) Slab moments at face of wall



(c) Distribution of moment in slab

FIGURE 3.2-2 DISTRIBUTION OF COLUMN/WALL MOMENT IN SLAB

When dealing with design of floors subject to actions from a dynamic analysis, the contribution of torsion of slab in resisting the applied moment may conservatively be disregarded. It may be assumed that the entire applied moment is resisted through bending of the slab. This is permissible, since in this case the presence of torsion is not essential for the equilibrium of the joint and the moments will be designed to account for the shortfall in torsion at the joint. For regular conditions one half of the applied moment may be assigned to each opposing face of the column for the design of the slab.

The breakdown of seismic moments to 50% on each opposing face of a column/wall will be too conservative where the aspect ratio (a/b in Fig. 3.2-1) of a column cross-section exceeds four. The seismic actions (moment, shear, axial) are generally reported at the center of column or wall interface with a slab. As indicated in Fig. 3.2-2, the magnitude of the resisting moments at the ends of the column/wall interface drop rapidly with increase in the length of the column/wall and slab interface. Based on the relative dimensions of the spans and the geometry of the column/wall and slab interface engineering judgment has to be used to consider a fraction less than 50% of the reported moment in design of the slab.

In the absence of better information, for panels with typical span to column dimension (in direction of span) less than 8, the fraction of moment to be resisted on the two opposing faces of a column may be reduced to less than 50%. .

The distribution suggested in the preceding is intended for typical interior columns/walls. At the exterior column/walls a larger fraction of the applied moment is resisted by the interior side of the connection. Figure 3.2-3 illustrates the approximated distribution of an applied unbalanced moment at an exterior connection with overhang. Again, in this instance too, for design purposes, the direct contribution of the torsion on the sides of the connection is disregarded.

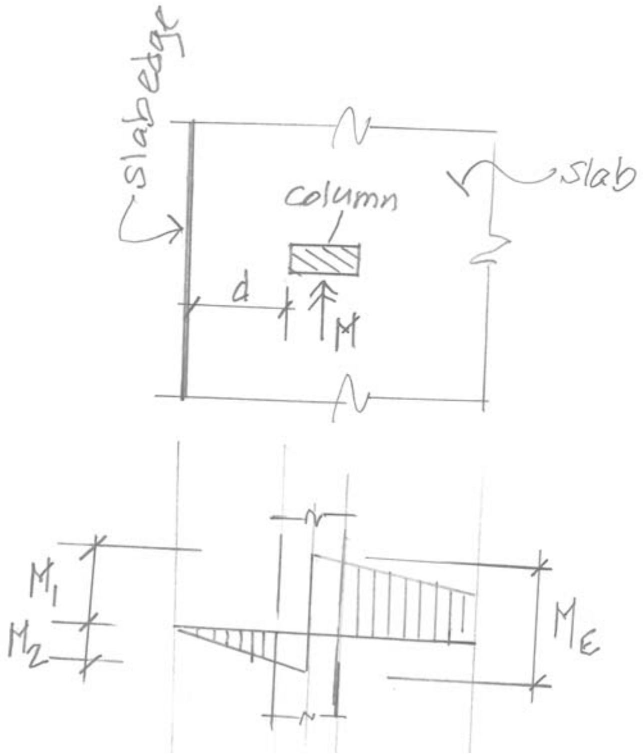


FIGURE 3.2-3 ASSUMED DISTRIBUTION OF MOMENT FOR AN EXTERIOR COLUMN/SLAB CONNECTION

For d >= 4*h M2 = 0.5*M1

For d< 4*h M2 = 0.5*(d/4h) * M_E

Where, h is slab thickness

Where the slab edge is provided with a perimeter beam, the full 50% fraction of the applied moment may be assigned to the overhang, provided the perimeter beam will be designed for the assigned torsion. Otherwise, the contribution of the perimeter beam in resisting the applied moment may be disregarded.

4 – DESIGN STEPS FOR FORCES AT SUPERSTRUCTURE/FLOOR CONNECTION

The following details the steps for design of floor slabs that receive seismic forces and are part of the primary lateral force resisting system of a building.

4.1 Design Steps for Floors Receiving Actions Derived from Pseudo-Static Solutions

Since the reported actions are a consistent set of forces resulting from the application of an applied lateral force, they may be viewed as a load case similar to any other load condition, such as live load. The lateral loads are treated in the analysis of the floor system alongside other loads and combined with other load cases, using the provisions of applicable building code. In this case, in addition to the applied moments from seismic effects, other actions of the lateral loads, such as axial force and shear will automatically be included in the analysis and their effects designed for. No simplification or approximations will be required. The lateral forces from a pseudo-static analysis in their entirety can be included in the analysis and design of a floor system.

4.2 Design Steps for Floors Receiving Actions from Dynamic Solutions

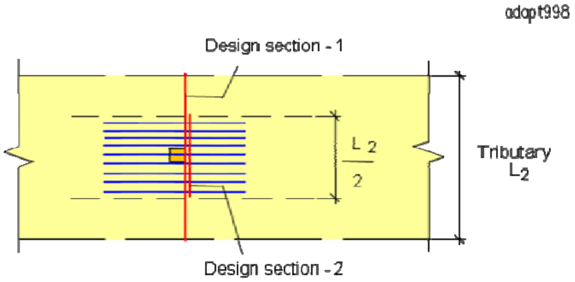
4.2.1 **Design for moments**

Option 1 – Integrated Approach

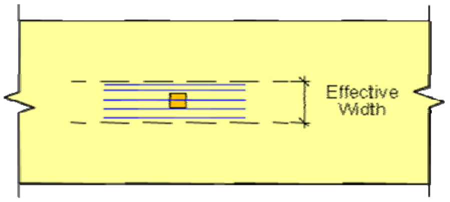
I. Perform the regular analysis of the floor system for the non-seismic forces, such as gravity and any other applicable actions, except for the seismic forces
II. Perform a design for the in-service (SLS) adequacy of the floor system. Add reinforcement where necessary.
III. Perform a design for the strength load combinations (ULS) of the floor system without the inclusions of seismic actions. Add reinforcement where necessary.
IV. Refer to the design sections at the faces of each column/wall (Fig. 4.2-1). Determine the value of the applied moment for each of the non-seismic load cases used in the analysis of the slab (MD, ML for dead and live moments, etc).
V. Distribute fractions of the seismic moments reported to on each side of the column/wall connections with the slab following the recommendations in the preceding.
VI. Determine the demand moment (Mu) at each face of the column/wall using the calculated moment at the face of the column/wall in (IV) and the fraction of seismic moment from (V), using the applicable code load combinations.
VII. Create a design section at the face of the column extending one-half of tributary (Fig. 4.2-1)
VIII. Calculate the design capacity (phi Mn) of this section, using the envelope of reinforcement reported in (II, and III).
IX. Compare the design capacity (phi Mn) from VIII with the demand moment from (VI)
X. If the calculated capacity exceeds the demand, terminate the calculation. Otherwise, proceed to the next step.
XI. Calculate the shortfall in capacity and determine the cross-sectional area of the reinforcement needed to match the demand.
XII. Place the reinforcement calculated in XI over the region shown in Fig. 4.2-2 and identified as effective width in Fig. 4.2-1. Extend the reinforcement one-sixth of the clear span from the face of the support. For overhangs, extend the reinforcement to one-half the length of overhang from the face of support.

Option 2 – Simplified Approach

I. Perform the regular analysis of the floor system for the non-seismic forces, such as gravity and any other applicable actions, except for the seismic forces
II. Perform a design for the in-service (SLS) adequacy of the floor system. Add reinforcement where necessary.
III. Perform a design for the strength load combinations (ULS) of the floor system without the inclusions of seismic actions. Add reinforcement where necessary.
IV. Refer to Section 3 and estimate the magnitude of the lateral moment on each side of a column or wall. Make sure that the lateral moment is factored (it is the design moment).
V. Determine the amount of non-prestressed reinforcement necessary to resist the moment obtained in IV.
VI. Place the reinforcement obtained in V at top and bottom of the slab to account for likelihood of change of sign in moments.

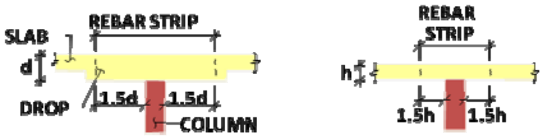


(a) Design sections for seismic reinforcement



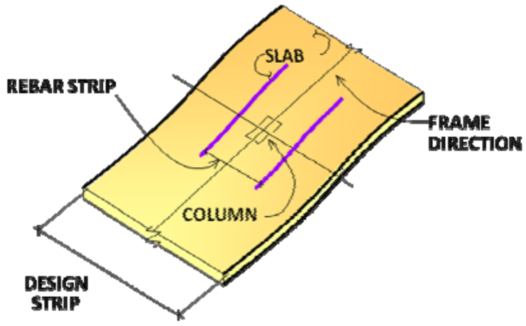
(b) Position of added reinforcement
For seismic effects

FIGURE 4.2.1-1 IDENTIFICATON OF DESIGN SECTIONS, MOMENT CAPACITY AND REINFORCEMENT STRIPS FOR SEISMIC ACTIONS



(a) SLAB WITH DROP

(b) FLAT PLATE



(c) VIEW OF A SLAB JOINT

FIGURE 4.2.1-2 IDENTIFICATION OF EFFECTIVE (REBAR) STRIP FOR PLACEMENT OF ADDED SEISMIC REINFORCEMENT

4.2.2 **Design for shear**

Shear force from seismic actions derived from dynamic analysis may be viewed as a concentrated local force that should be detailed for proper dispersion into the slab.

4.2.3 **Design for Axial Load at Superstructure/Floor Connection**

Under the action of horizontal forces from seismic effects, the sum of vertical forces on a supporting floor system would be zero. When using forces derived from pseudo-static analysis, the forces can be directly applied as input to the analysis of the floor system and combined with other actions for design. Since for the actions obtained from a dynamic analysis, the axial force given from one column/wall connection does not correlate, either in sign, nor in load case to other column/wall connection forces, using engineering judgment each vertical action has to be viewed in isolation for the impact on the vicinity of its point of application. This includes punching and safe dispersion over an appropriate area. The moment generated in the slab as a result of the application of the vertical components of the seismic effects cannot be estimated reliably for actions derived from dynamic analysis. Engineering judgment has to be exercised to add reinforcement, where the bending effect of the axial force is deemed significant.