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Structural Evaluation and Remediation of Floor Slab Deflection

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Abstract

A 4-story reinforced concrete structure built above an underground parking garage shows some slab deflections, and the deflections of the concrete floor slabs are proposed to be alleviated by the application of light-weight topping material in conjunction with localized strengthening of the slabs. The application of light-weight concrete topping on the existing slab has been simulated and its performance to anticipated loads has been analyzed. The application of light-weight topping material imposes additional weight on the exiting floor slabs. This added weight on the existing slabs causes over-stressing of the slabs. This over-stressing can be alleviated by enhancing the load carrying capacity of the existing slabs. Additional load carrying capacity in the existing slabs can be developed by localized strengthening of the slabs utilizing techniques such as the application of fiber-reinforced composites on the bottom surface of the slabs, and application of fiber-reinforced composites adequately complements the capacity of the existing slabs to bear the additional load imposed by light-weight leveling material. Additional moments in the beam and columns induced by the application of the light-weight topping material were tabulated and compared with capacity. The moment D/C ratios of the beam and columns are well the range of acceptable limits, and the beam and columns are not overstressed by the application of the surcharge.

Keywords: slab deflections, light-weight concrete topping, fiber-reinforced composite

1. INTRODUCTION

In the past several decades, excessive slab deflection has been a main issue for homeowners and tenants, and much progress has been made in the development of methods for structural evaluation and remediation of concrete slab deflection. A 4-story reinforced concrete structure built above an underground parking garage that was built in the early 1980's shows some slab deflections, and the existing deflections in the concrete floor slabs at the second and third floors of the building are proposed to be leveled by the application of light-weight topping material in conjunction with localized strengthening of the slabs. Proposed areas for slab remediation at the second and third floors are shown in Figures 1 and 2, respectively.

To obtain realistic results, a thorough analysis of all factors is required - the strength of existing floor slab, method of remediation, additional deflections due to floor leveling material, and additional moments in the beam and columns due to floor leveling material. Our evaluation included a visual observation of the conditions at the site; a testing program to determine the amount and location of reinforcement bars within the second and third floor slabs at locations of worst deflection; and a SAP2000 (2001) computer analysis of the forces in the slabs and their load-carrying capacities

2. STRUCTURAL EVALUATION

A detailed SAP2000 (2001) computer model of the entire building was created to perform a structural evaluation of the second and third floor slabs in their "as-built" condition. Another model was created with the second and third floor slabs loaded with a simulated load equivalent to the added weight due to the floor leveling material that would be used to re-level the two floors. Columns and beams were modeled with frame elements, floor slabs and walls were modeled with shell elements. Figure 3 shows a view of the computer model. A very fine mesh was used to represent the second and third floor slabs to accurately capture the force distribution in the slabs.

(1) LOAD APPLICATION

The amount of floor leveling material to be applied to the areas defined in Figures 1 and 2 was determined from the results of an earlier manometer survey of the second and third floor slabs. The application of the light-weight topping material in the new areas was specified such that the modified finished floor elevation would be within typical industry-standard tolerance limits. Typical industry-standard tolerance limits for concrete floor slabs (ACI 117-90 1990) is ¾ inches above and below the theoretical elevation plane.

Seismic loads were applied by subjecting both models to the 1997 Uniform Building Code (UBC 1997) design basis earthquake ground motion response spectra adjusted for site soil type and site distance from the known seismic faults. Load combinations defined in the UBC (1997) were used for the evaluation of the forces in the slab.

(2) ANALYSIS OF SAP2000 COMPUTER MODEL

Slab forces at the middle and column strips in all areas of proposed floor leveling were extracted from the analysis and the force demand was compared to the load-carrying capacity of the existing slabs. Results obtained from the first analysis of the "as-built" building indicate that the capacity of the exiting slabs, without any light-weight topping material, is adequate for resisting the dead loads that are currently imposed on them. As such the deflected slabs do not pose a concern for life safety. The deflections of the slab do not affect their load carrying capacity but affect their serviceability. Results from the second model with the simulated weight of the light-weight topping indicate that the combined loads will exceed the existing moment capacity of the slabs. Several load cases including dead, live, partition, surcharge loads due to application of light weight concrete topping and UBC 1997 code spectrum were defined in the SAP2000 (2001) computer models. From the analysis it was determined that the load combination of dead plus live loads only was the critical load combination for all areas of the slab that are being leveled. In these localized areas, remediation measures to strengthen the slabs will thus have to be adopted prior to the application of the floor-leveling compound. The best strengthening method for the concrete slab at these locations is to use a thin layer of fiber material that would be applied on the bottom surface of the concrete slabs at mid-spans where strengthening is needed. These areas of "high tech" material would provide the needed strength for the slab to sustain Code loads. For example, the TYFO® Fibrwrap® Fiber-Reinforced composite system (2001) can be used to strengthen the slabs.

(3) SAMPLE ANALYSIS OF SLAB LOAD-CARRYING CAPACITY AND STRENGTHENING

A sample calculation is provided to illustrate the procedures for the design using the Fiber-Reinforced Composite System (2001) for flexural enhancement due to moments about X-axis at the middle strip of the third floor bounded by gridlines B-C and 1-2.
The typical slab cross-section at the second and third floor is shown in Figure 4. The thickness of the existing slab in 8.5 inches, the bay is 28 feet square, the middle strip reinforcement is #5 bars at 14 inches on center, each way. For the design of Fiber-Reinforced Composite System (2001), the following procedure is used.

- Design Procedure:
  A. Calculate Moment Capacity of Existing Slab Section without Composites:
  B. Calculate Strains Under Existing Loads
  C. Estimate Required Number of Composite Layers
  D. Check Moment Capacity of Strengthen Slab
     a) At Limit State for Ultimate Compressive Concrete Strain (Concrete Crushing at 0.003)
     b) At Limit State for Maximum Allowable concrete Tensile Strain (0.004)

Figure 5 shows the strain and stress diagram at various stages of loading for the cross-section as a sample.
As a calculation result, two layers of TYFO® Fibrwrap® System (2001), SCH-41 are used with 64.3% of the bottom face of the slab covered with composite layers.

The same process can be repeated to determine the amount of strengthening at other locations of the second and third floor slabs, and detailed instruction for installation of fiber reinforced composite system at the middle strip of the third floor bounded by gridlines B-C and 1-2 are shown in Figure 6 as example.

(4) VERTICAL DEFLECTIONS AT THE SLAB MID-POINT

ACI 318-99 (1999) specifies minimum concrete slab thickness for control of two-way slab deflections. If the slab thickness equals or exceeds the specified minimum thickness, defections need not be computed, and serviceability in terms of deflection control is deemed to be satisfied. However, the minimum thickness of slab for this building is $1/33^{rd}$ the clear span (28/33x12 = 10.2"), which is larger than the real slab thickness of 8.5" of the building, therefore, the concrete floor slab should meet code specified serviceability requirements in terms of vertical slab deflections. Code specified limit of L/240 in the 1997 Uniform Building Code (UBC 1997) and ACI-318-99 (1999) can be utilized for serviceability problem. Expected total slab deflection combining immediate deflection caused by the sustained load and long-time deflection due to creep and shrinkage can be compared with code specified limit of L/240 and real slab deflections in the building. The use of a multiplier applied to immediate deflection provides a simple calculation procedure for long-time deflection due to creep and shrinkage, and ACI 318-99 (1999) suggests a sustained-load multiplier of 2 applied to immediate deflection for the case of no compression reinforcement. The 1997 Uniform Building Code (UBC 1997) also provides same long-time deflection multiplier with ACI 318-99 (1999). ACI 435R-95 also outlines procedures to evaluate the long-term deflections of a two-way slab. In order to estimate these long-term deflections, parameters such as the ultimate creep coefficient C_u, and ultimate shrinkage strain, $(\varepsilon_{sh})_u$ are required to be estimated. It is also stated in Section 2.3.4 of ACI 435R-95 that "ACI 435 (1978) suggested that the average values for C_u (ultimate creep coefficient of concrete) and $(\varepsilon_{sh})_u$ (ultimate Shrinkage strain of concrete) can be estimated as 1.60 and $400x10^{-6}$, respectively." Using the average values of C_u and $(\varepsilon_{sh})_u$, expected slab deflections based on ACI 435R-95 (1995) were evaluated. Calculated values form code specified limit of L/240 and expected total slab deflections combining immediate deflection and long-time deflection based on the suggested long-term multiplier 2 of ACI 318-99 (1999) and long-term deflection evaluation procedure in ACI 435R-95 (1995) quite similar to each other, but the real slab deflections are greater than code specified limits. However, some researchers have found that the multiplier of 2 to be low and have recommended higher long-time deflection multipliers as high as 4 (ACI 435.9R-91 1991).

The vertical deflections at the slab mid-point due to the application of the individual static load cases in the regions where the light-weight topping material is to be applied are tabulated. The deflections from the individual load cases can be combined using the load factors listed below to determine the total deflections. The load combinations used to evaluate the slab deflections are:

1.4D+1.7L
1.1(1.2D+0.5L+1.0E)

The slab deflections due to the both load combinations were computed. Based on the calculation result, the additional deflection imposed by the application of the light-weight topping material are a small percentage of the deflection caused by the existing dead and live loads.

The ratio of the slab deflections with and without the surcharge imposed by the light-weight topping material has a maximum value of 1.15, implying that the deflection of the slab increases by an additional 15% because of the surcharge. However, the application of the fiber composite material on the bottom surface of these affected slab areas enhances the stiffness of the slab and thereby assists in the controlling the additional deflection likely to be imposed by the application of light-weight topping. A simple calculation of the transformed moment of inertia can be performed to illustrate the increase in the slab stiffness due to the application of the fiber composite. For a cracked slab with no fiber composite, the transformed moment of inertia of the cracked section, I_{cr}, is 1025.8 in^4, and for a cracked slab with 1 layer of fiber composite, the transformed moment of inertia of the cracked section is 1320.8 in^4. The ratio of the transformed moment of inertia with (I_{cr}') and without (I_{cr}) fiber reinforcement is 1320.8/1025.8=1.29, which far exceeds the maximum ratio of the displacements 1.15. Therefore, it can be concluded that the addition of light-weight material on the existing slab will not increase the existing deflections.

(5) STRENGTH OF EXSISTING BEAMS

Moment demands in the beams adjacent to the areas of light-weight topping application were compared to the beam capacities. The beams have five different cross section types and the moment capacities of the beams were determined as the yield moment from a moment curvature analysis. The moment in the beams due to the application of static loads and the positive and negative moments in the beams induced by seismic forces in the presence and absence of the light-weight topping material in the regions where the light-weight topping material is to be applied checked from SAP2000 (2001) output.

From the result, it was determined that the moments in the beam due to the seismic load combination is more critical and the additional moments induced by the application of the light-weight topping material are a small fraction of the moments caused by the existing dead and live loads.. Only the negative moment demand for one beam type exceeds its moment carrying capacity. It is to be noted that these beams frame into the drop panels of the columns and additional capacity will be provided to the beams by the drop panels. The contribution of the drop panels was not included in the moment capacity calculations of the beams. In addition the ratio of the moment demand on the beams, with and without the additional weight imposed by the light-weight topping is only 1.01, i.e., an increase of only 1%. Hence it can be concluded that these beams will not be overstressed by the application of the surcharge.

It should be noted that the application of the fiber-reinforced composites was necessary to provide additional moment capacity to the slabs for serviceability load conditions and not for seismic loads. The moment capacities of the slabs reinforced with fiber composites will be enhanced after the application of the composites. The enhanced capacities of the slabs were not incorporated in the computer analysis and therefore the reinforced slabs will carry a larger fraction of the moment and further relieve the moment demands in the beams, thereby further reducing the difference in D/C ratios from both cases.

(6) STRENGTH OF EXSISTING COLUMNS

Axial force interaction with biaxial moment demand in the columns adjacent to the areas of light-weight topping application was evaluated. The column elements below the second and third floors were analyzed since the weight of the surcharge will be borne by these columns. The axial force with biaxial moment interaction diagrams for the column cross-sections were obtained using the computer program PCACOL (Portland Cement Association, 1993). The result from the PCACOL (1993) axial-load moment interaction analysis for Column Type L2 (22"x22", 12#9 reinforcing steels, #4@3" ties) is shown on Figure 7 as example. The axial force and moment about both axes at each end of the columns were checked from SAP2000 (2001) output.

The column demands were externally checked against capacities for the SAP2000 computer models. The demand was checked with the capacity based on Eq. (1).

$$\frac{1}{P_{ni}} = \frac{1}{P_{nx}} + \frac{1}{P_{ny}} - \frac{1}{P_o} \qquad (1)$$

where,

P_{ni} is the nominal axial load strength at given eccentricity along both axes.
P_o is the nominal axial load strength at zero eccentricity.
P_{nx} is the nominal axial load strength at given eccentricity along x-axis.
P_{ny} is the nominal axial load strength at given eccentricity along y-axis.

A post-processor was developed to analyze the force output of columns to check the axial force and biaxial bending moments in the column elements against the column P-M interaction diagrams for each load combination. The post-processor outputs the elements for which the demand exceeds the capacity. The critical load combination was determined to be case with seismic forces. Since the output forces from a response spectra analysis are positive, the response spectra forces corresponding to loads UBC-SB-X, UBC-SB-Y, UBC-SC-X and UBC-SC-Y were both added and subtracted from the output forces from the other loads to determine the worst case combination. The post-processing was performed for cases with and without the surcharge load applied as the result of application of the light-weight topping. From the comparison of demand capacity ratios from cases with and without the surcharge load, it can be determined that the D/C capacity ratios in all except 9 columns are the same as they were prior to the application of the light-weight topping material. The reason for the D/C ratio larger than 1.0 can be attributed to the fact that the seismic loading on the building according to current codes is larger than what it was when the building was originally designed. According to the 1997 Uniform Building Code (1997), the factored load combinations for seismic loads on a concrete building were multiplied by a factor of 1.1. It has been determined by SEAOC that the 1.1 multiplier should not be applied (1999 SEAOC Blue Book, page 86). In the nine columns where the loads in the case with the surcharge exceed the loads in the case without surcharge, the exceedance percentage is only 5%, which is well the range of acceptable limits.

(7) STRENGTH OF FOUNDATIONS

Since the loads on the beams and columns has essentially remained unchanged with the application of the light-weight topping and composite fiber reinforcement to the slabs, it can be inferred that the capacities of the foundations will not be adversely affected by the proposed rehabilitation work.

3. CONCLUSION

Based on the evaluation of the exiting building including a visual observation of the conditions at the site; a testing program to determine the amount and location of reinforcement bars within the second and third floor slabs at locations of worst deflection; and a SAP2000 computer analysis of the forces in the slabs and their load-carrying capacities, the deflections of the concrete floor slabs on the second and third floors are proposed to be alleviated by the application of light-weight topping material in conjunction with application of fiber-reinforced composites. Application of properly calculated and placed fiber-reinforced composites will adequately complement the capacity of the existing slabs to bear the additional load imposed by light-weight leveling material. Additional deflections due to floor leveling material are a small percentage of the deflection caused by the existing dead and live loads, and the ratio of the transformed moment of inertia with (I_{cr}') and without (I_{cr}) fiber reinforcement far exceeds the maximum ratio of the displacements. Based on the moment demand comparison with and without the surcharge for beam and moment D/C ratio comparison with and without the surcharge for columns, beam and columns will not be overstressed by the application of the leveling material and the exceedance percentage is the range of acceptable limits.

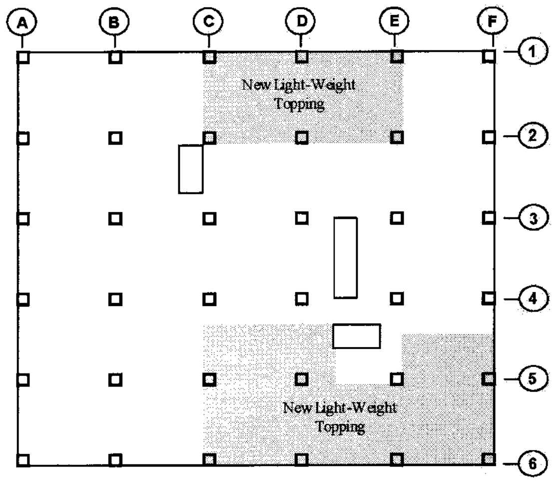

Figure 1. Second Floor Plan Indicating Proposed Areas of Floor Leveling

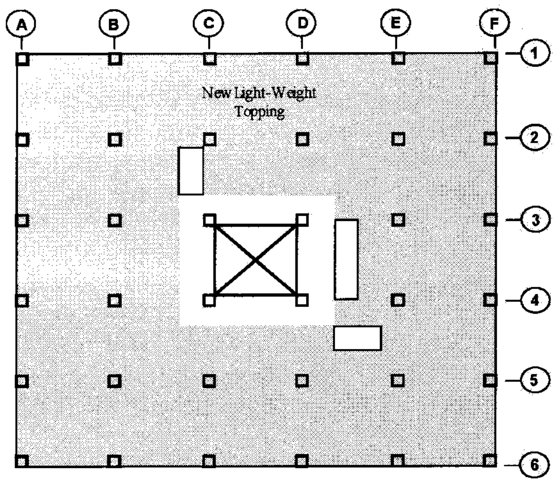

Figure 2. Third Floor Plan Indicating Proposed Areas of Floor Leveling

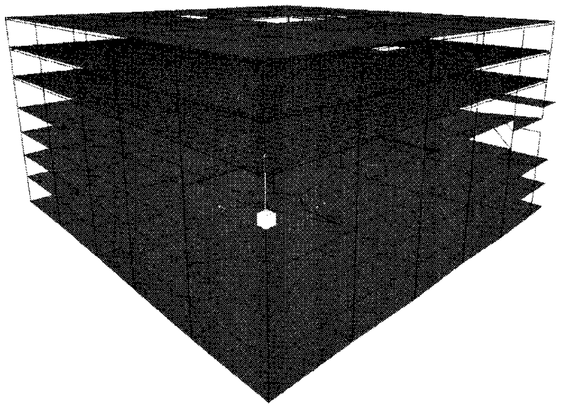

Figure 3. View of the Computer Model

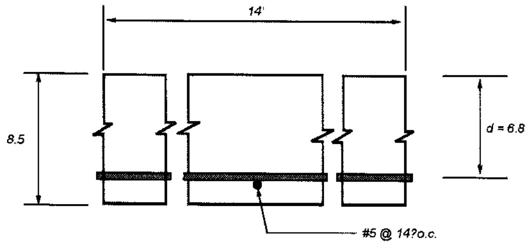

Figure 4. Slab Section

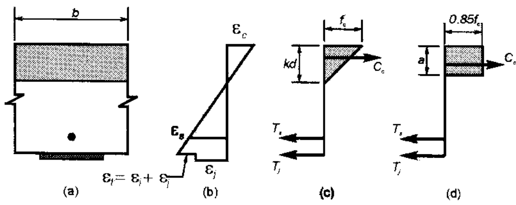

Figure 5. (a) Slab Section with Composite Layer, (b) Strain Diagram, (c) Stress Diagram in Linear Range, (d) Stress Diagram at Ultimate State

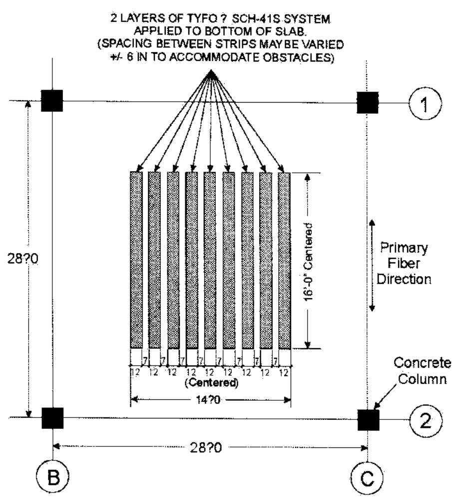

Figure 6. Fiber Reinforcement at the Third Floor Bounded by Gridlines B-C and 1-2

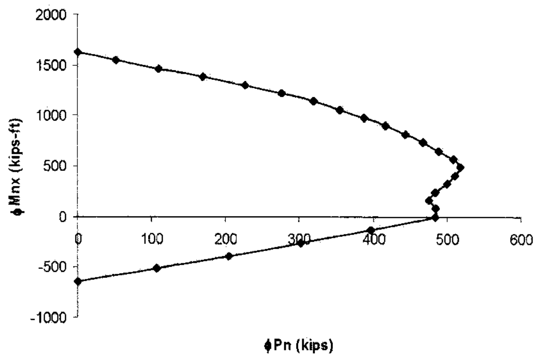

Figure 7. P-M Diagram for Column Type L2

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