Strengthening and Load Test Evaluation

By Tarek Alkhrdaji and Jay Thomas

The continued economic growth of the United States presents the concrete repair industry, engineers, and contractors with distinctive challenges arising from the increasing need to evaluate and implement effective and economical strengthening techniques to resolve load capacity deficiencies. A significant number of buildings in downtown areas, especially in big cities along the East Coast, were constructed during the first half of the 20th century. For most of these buildings, the original structural drawings are not available, and the composition of their structural elements and the strength of the materials used during construction are not known. Most of these older buildings have high floor loading, high ceilings, large spans, and extra roof space for auxiliary power equipment, which make them very attractive for housing telecommunications facilities. In many cases, the floor live load demands for such a facility exceed the capacity of the building. Due to economic and historical reasons, the current trend is to strengthen these structures rather than replace them with new ones. The challenge is that the strengthening system needs to be tailored to serve the new intended use of the structure without interfering with its function or disturbing the tenants occupying other portions of the structure.

Telecom hotels are cropping up in downtown areas all across the country as expanding technology firms need to meet increasing demands. Telecom hotels are essentially warehouse spaces for Internet-related telecommunications and other high-tech equipment that usually need to be located near a high bandwidth connection, such as a fiber-optic network. These telecom hotels present a unique set of opportunities and challenges to the concrete repair industry. Telecommunications equipment typically requires structural floor capacity in the range of 125 to 175 pounds per square foot (psf). This live load requirement exceeds the design loads of many of the older buildings. Due to the conservative design approaches used by engineers at the beginning of the 20th century, it is very common to find that these structures will be able to carry the new loads if some of the structural members are strengthened. In many instances, in-depth investigations of the structural requirements for the new service loads can reveal that the deficiencies are limited to a number of structural elements rather than the entire structure.

No matter what strengthening technique is used, the ability of the elements to perform as an integrated system can only be achieved by providing an adequate bond between the existing concrete member and the externally or internally applied strengthening system. This task is not easy considering that there are no simple, straightforward design and execution methods for strengthening projects. This process is further complicated by the fact that the strengthening of older structures usually involves limited information on their structural systems, thus requiring more detailed investigation to verify the unknown and assumptions regarding the health and condition of the structural components.

Strengthening with Structural Overlay

Structural strengthening of reinforced concrete (RC) members using section enlargement, one of the oldest strengthening techniques known to the concrete construction industry, involves the placement of additional concrete on an existing structural member in the form of an overlay or jacket. The additional concrete is typically structural (reinforced) concrete designed to be a load-carrying element. With this method, columns, beams, slabs, and walls can be enlarged to add load-carrying capacity or to increase stiffness.

An additional structural concrete slab bonded on top of the existing slab can increase the structural capacity of the supporting beams or joists by increasing the effective depth of reinforcement at the positive moment region (typically at midspan). With the addition of steel reinforcement, the overlay can increase the structural capacity at the negative moment region (typically at supporting beams). In all cases, the designer should incorporate the weight of the additional concrete overlay/jacket in the design of the enlargement.

This strengthening technique is more appropriate for members in which increasing the effective depth of the reinforcement is sufficient to cancel out the effect of the overlay weight. The composite behavior of the strengthened element can only be taken into account if monolithic structural action is assured. Good composite behavior requires good bonding of existing to new concrete to ensure adequate shear transfer at the bond interface, which must not deteriorate under cyclic traffic loads, shrinkage, and temperature loads. If the concrete at the surface of the member is weak and does not have adequate strength, the weak concrete should be chipped away. Steel shear dowels may also be used to enhance the composite behavior. Strengthening

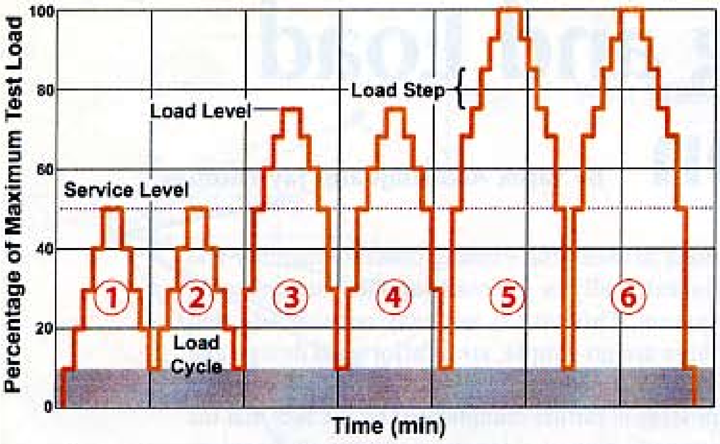

Fig. 1: Load steps and cycles for a cyclic load test

with reinforced concrete overlay is relatively easy, economical, and effective. However, inexperienced workmanship can actually worsen the structural condition by producing additional dead weight to the already deficient slab. Quality control in the form of bond tests is critical.

Preliminary Investigation

The capacity of an RC member can be calculated if sufficient information regarding the material properties and reinforcement layout are available. This information can be verified through a field investigation program that may involve concrete testing, collecting and testing steel coupons, and using various destructive and nondestructive techniques to determine the layout and spacing of the reinforcement. Even with such intensive investigation, the results may not be conclusive.

During the first quarter of the 20th century, more than a hundred different proprietary systems of reinforcement and patented reinforcing bars existed, which made this type of construction rather confusing. Some of these systems are mentioned in the Concrete Reinforcing Steel Institute's booklet, *Evaluation of Reinforcing Steel Systems in Old Reinforced Concrete Structures*. Analysis of a concrete structure framed with one of these proprietary systems is difficult even when the original plans are available. As a result, we see an increasing number of cases in which the owner requests a load test to verify the capacity improvement of the strengthened structure. Engineers may also specify a load test to ensure that no unforeseen failure modes will take place. Load testing can be used to evaluate the performance of repaired or strengthened structural members and to prove the effectiveness of new structural upgrade technologies, such as externally bonded fiber reinforced polymer (FRP) reinforcement. Load testing is a method of evaluation that may be more representative of the performance of the structural member than analytical approaches, and it can provide valuable information regarding the health and performance of a strengthened structural element.

Load Testing for Strength Evaluation

The preliminary steps in the planning of a load test are independent of the test type. These steps are defined by ACI Committee 437 (1991), and guidelines for the condition evaluation are given in ACI 364.1R, *Guide for Evaluation of Concrete Structures Prior to Rehabilitation* and in SEI-ASCE 11-99, *Guideline for Structural Condition Assessment of Existing Buildings*. An understanding of what is and is not known about the structure should be established. This is achieved by studying existing drawings, reports, and calculations, and is verified by an on-site inspection.

A constant concern during a load test is the safety of persons performing the test and the safety of the structure. The use of scaffolding, shoring, straps, or chains may be a key item in preventing the collapse of the member if a premature failure should occur. The strength of the shoring should be adequate to carry the weight of the test area plus the applied test loads. All of the floors below the test floor that cannot carry the weight of falling concrete and superimposed test loads should be shored, all the way down to the foundation level, if deemed necessary.

Historically, loads in the form of water pools, sandbags, and concrete or steel blocks have been used to load test structures. Cyclic in-situ load testing (also referred to as a rapid load testing) takes the same approach to loading a structure and measuring its response.

A cyclic load test consists of concentrated loads applied in a quasi-static manner in at least six load cycles, with each cycle containing several load steps (Figure 1). Each load step is maintained until the member has displayed its stability, at which time the load is increased. In this manner, the maximum applied load is approached gradually, which provides an inherent safety mechanism within the load testing protocol. Each load cycle is repeated in order to provide a better understanding of the behavior of the member under the test loads. Because data is collected continuously from a variety of instruments, the engineer has the opportunity for real-time evaluation of the behavior of a structural member.

Evaluation of the cyclic load test is achieved by examining the structural response at every load level. Stability of the structural response parameters (for example, repeatability, deviation from linearity, and permanency) under a constant load demonstrates the member's ability to safely maintain that load and gives an indication of the behavior of the test member.

When compared with the traditional approach, the cyclic load-testing procedure allows for evaluation that can be carried out in a fraction of the time and may supply more valuable information. This load-testing procedure was evaluated by Concrete

Innovations Appraisal Services (CIAS), a wholly owned subsidiary of the Concrete Research and Education Foundation (ConREF), in the *Guidelines For Rapid Load Testing of Concrete Structural Members*. This evaluation indicated that this method "...has potential for making load testing of new structures, deteriorated structures, and repaired structures more practical and more meaningful."

Case Study

The following case study discusses the strengthening and cyclic load testing performed on the second-level structural floor of a building located in downtown Cleveland, Ohio. The nine-story building was constructed in 1917. Originally, the second floor of the building was occupied by a department store. With the high percentage of Internet traffic between New York and Chicago running through fiber-optic lines, downtown Cleveland is becoming a prime location for the telecom industry. To meet the demands of this industry, the owner of the building decided to upgrade the floor on the second level to house telecommunications equipment.

Building Description

The building was constructed with masonry over a concrete-encased steel frame and a reinforced concrete floor system (Figure 2). The ceiling height is approximately 14 ft, and the column spacing varies from 19 to 23 ft. Due to the age of the building, very limited construction and maintenance records were available. The existing engineering drawings provided only floor plans and geometry of the members. No information regarding material properties or reinforcement details were available. All dimensions and section geometries were field-verified.

The floor system consists of reinforced concrete joists supporting a concrete slab monolithically cast with the joists. The concrete slab is 3.5 inches thick and reinforced with No. 3 steel bars spaced at 18 inches on the centers. The joists are 27.6 ft long, 6 inches wide, and 15.5 inches deep. Field investigation of the joists revealed that they are typically reinforced with two 1-inch square bars at the midspan, one of which is bent up at approximately 5.5 ft from each end and extends above the support. There was no information on reinforcement details at the supports. Field investigation revealed that an additional straight bar is provided over the support at the location of the bent-up bars. No information on material characteristics was available for the joists. Due to time limitations, a nominal concrete strength of 3,500 psi and steel yield strength of 33,000 psi were assumed for preliminary analysis of the joists. These values were based on the typical material strength used at the time the building was constructed as well as the observed field condition of existing concrete. The assumed values were later confirmed through load testing.

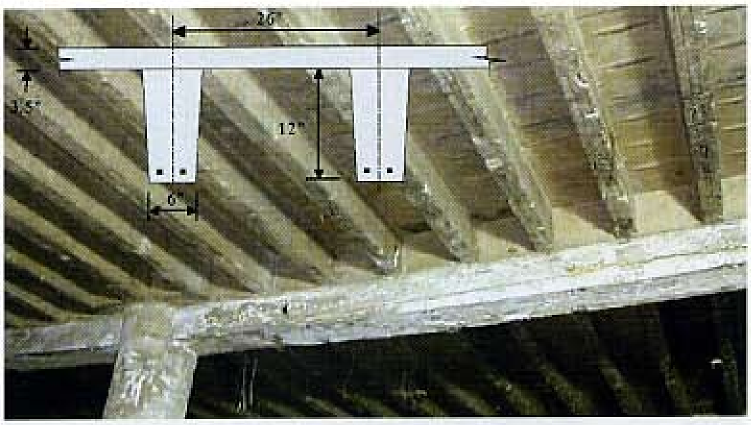

Fig. 2: Floor system

The self-weight of the original slab/joist system was calculated to be 86 psf. Site investigation of the joists revealed that the joists do not have any steel shear reinforcement. Accordingly, the shear strength was determined using the geometry and assumed material properties of the joists. The flexural capacity could not be determined accurately due to unknown end conditions, specifically the reinforcing steel layout at the joist supports. Preliminary analysis of the existing floor system indicated that the existing beams and slab are capable of carrying the proposed loads. The joists, on the other hand, were deficient in both flexural and shear strengths. Results indicated that the existing live load capacity of the floor is approximately 96 psf, governed by the shear strength of the joists. To house telecommunications equipment, the floor needed to be upgraded to carry its self-weight, a superimposed dead load of approximately 25 psf, and a service live load of 150 psf acting over the entire surface of the floor. The superimposed dead load is a result of the concrete overlay required to level the poor condition of the concrete slab surface.

Strengthening and Load Testing

Cyclic load testing was performed and evaluated following the procedure set forth in CIAS' appraisal report. The cyclic load tests did not seek to evaluate the safety or the load-carrying capacity of the entire structure. Rather, it was designed to locally verify the performance of some typical joists that appeared to be the "weakest link." To this effect, the joists were loaded near their ultimate strength, and their response was measured in terms of deformation and crack width.

The cyclic load-testing procedure involved applying concentrated loads to the test joists at predetermined locations to simulate the effect of maximum flexural forces at midspan and maximum flexural and shear forces at the supports of the test joists. Loading was achieved using hydraulic jacks that are relatively easy to install and control. This load-testing procedure provided a higher safety level due to the ability to remove loads rapidly. In

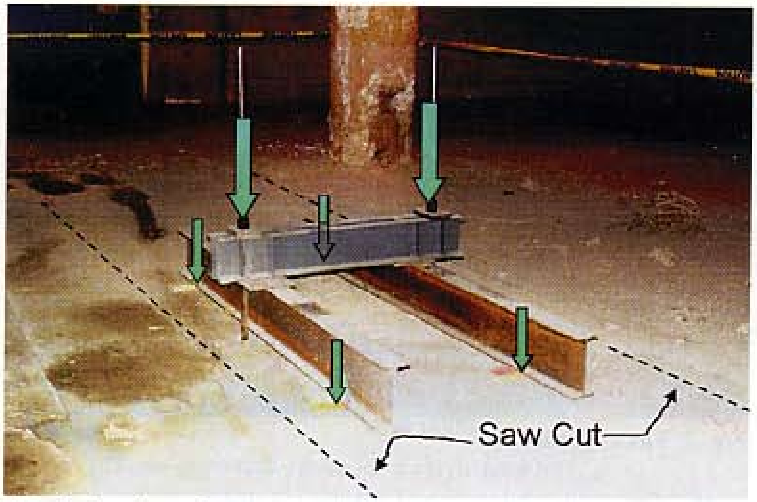

Fig. 3: Load transfer to test joists

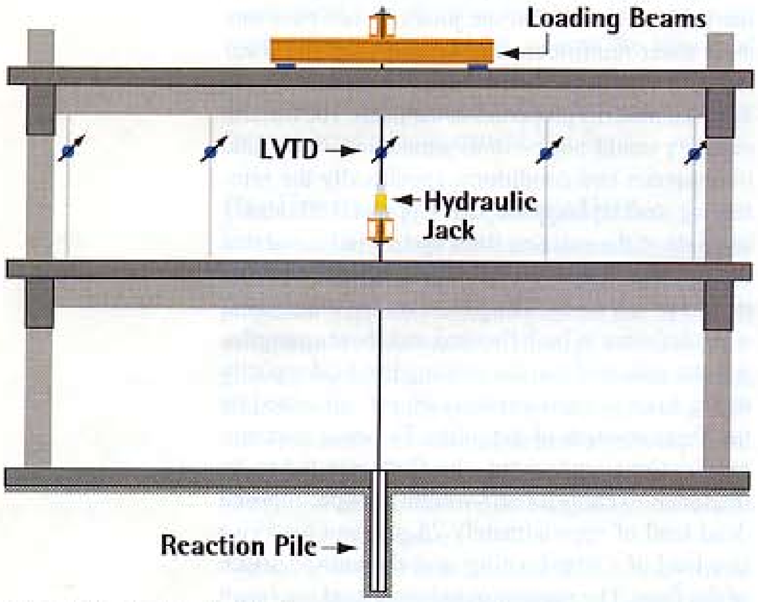

Fig. 4: Cyclic load test setup

addition, in the event that permanent damage was done to the test members, this damage would be limited to the localized area of the structure and could be repaired after the test was completed. Loading the joists to levels near their strength provided further evidence that the strengthening system is not likely to fail due to any unforeseen failure mode. The response of the joists in the vicinity of the applied loads was monitored throughout the tests and used to evaluate their performance and strength.

Analytical modeling of the joists indicated that the maximum moments and shear forces calculated using ACI 318-99 could be produced using two-point loads spaced 6 ft apart (Figure 3). This loading configuration produced the target moment force at midspan as well as moment and shear forces at the supports of the joists. The load was applied using hydraulic jacks that pulled against a reinforced concrete micropile cast into the ground on the floor below to provide reaction to the jacks (Figure 4). A high-strength steel bar was used to connect the jacks to transfer the load to the micropile. Linear variable differential transformers (LVDTs) were used to measure joist deflections at five locations along their lengths. A load cell was used to measure the applied load. Measurements were collected using a data acquisition system that allowed for real-time monitoring of the applied load and the behavior of the test joists. During the test, deflections and crack width were monitored for stability.

Three load tests were performed on the joists. Test 1 was performed on two joists that were isolated by saw-cutting the concrete slab along a line between the joists. Prior to testing, the joists were strengthened for shear using carbon FRP strengthening systems applied in the form of U-strips 12 inches wide and spaced at 18 inches on centers (Figure 5). Each strip extended over the sides and the bottoms of the joists. The strips were applied over a 10-ft length at each end of the joists. The load test was terminated when the midspan deflection became unstable and inelastic behavior was observed. Large residual deflections were measured when the load was removed. Based on the test results and per ACI 318-95 building code, the joist was rated for a superimposed dead load of 25 psf plus a live load of 135 psf. The shear performance was adequate, with no shear cracks or failure signs observed.

Results of the first test indicated that failure of the joist was governed by yielding of reinforcement at the support. No failure signs were observed at the joists' midspans. To address this deficiency, it was proposed to use a bonded, reinforced overlay instead of just a bonded overlay. The proposed overlay consisted of 3-inch-thick concrete overlay reinforced with 6 x 6-inch, w7.5 x w7.5, steel wire mesh. To ensure adequate bond between existing and new concrete, the slab surface was prepared by aggressive abrasion blasting to remove all weak concrete and provide an open-pore structure. This allowed the new concrete to bond to the prepared surface through mechanical interlock. Pull-off tests were performed on the overlay, and test results indicated that failure occurred at surfaces other than the interface surface at a stress higher than that specified by ICRI guidelines.

After the overlay was applied, Test 2 was performed on the same two joists to verify the overall behavior of the strengthened system. The test was performed following the same procedure outlined earlier. However, the joists were only loaded to 85% of the ultimate, as recommended by ACI 318 to prevent excessive damage of the joists. During testing, a number of flexural cracks developed on top of the slab (through the overlay) at both ends of the joists (at the negative moment region). The number and distribution of the cracks indicated that sufficient bond was present between the existing and new concrete. Thus, a composite behavior was achieved. The load test results illustrated an improvement in the stiffness and deflection behavior of the joists after strengthening. Based on the test results, the strengthened joist was rated for the self-weight plus 36 psf superimposed dead load (RC overlay) and 150 psf live load, the target service load for the telecommunications equipment.

The addition of the reinforced overlay increased the shear strength of the joists by increasing the depth of the internal steel reinforcement; therefore, less shear reinforcement was required to meet shear force demands. As a result, the configuration of CFRP shear reinforcement was changed from a CFRP U-strip configuration to CFRP strips applied only to the sides of the joist stems (Figure 5). This resulted in optimized strengthening that significantly reduced labor costs, as rounding of the corners of joist stems was not necessary. Test 3 was performed on an isolated joist to determine its performance with carbon FRP strips applied to the sides only. The joist was not tested prior to strengthening to verify the behavior without any previously induced damage. Results of the load test showed improved stiffness of the joist and adequate shear performance with no shear cracks observed (Figure 6). Based upon the acceptance parameters set by the CIAS appraisal report, the performance of the joist was satisfactory for that load level.

Proven Technique

Evaluation and strengthening of concrete structures is an art form that has evolved into a complex science. It involves the use of conventional cement-based materials, advanced composite materials, and new techniques and technologies for condition assessment and strength evaluation. When properly applied, strengthening with RC overlay is relatively easy, economical, and effective, and can increase the flexural and shear strengths of structural members. Strengthening design and assessment is infinitely more complex than new construction and should not be treated lightly. In addition to the unknown actual structural state, the degree to which the new materials and the existing structure share the composite system must be evaluated. Unfortunately, a prescription to guarantee a final product does not exist. Often, despite the use of novel materials, ineffective strengthening can result from a combination of poor installation and inappropriate assumptions about the existing condition of the structure. Load testing is a method of strength evaluation that is more representative of the performance of the strengthened structural member than analytical approaches and can provide valuable information regarding the health and performance of a strengthened structural element.

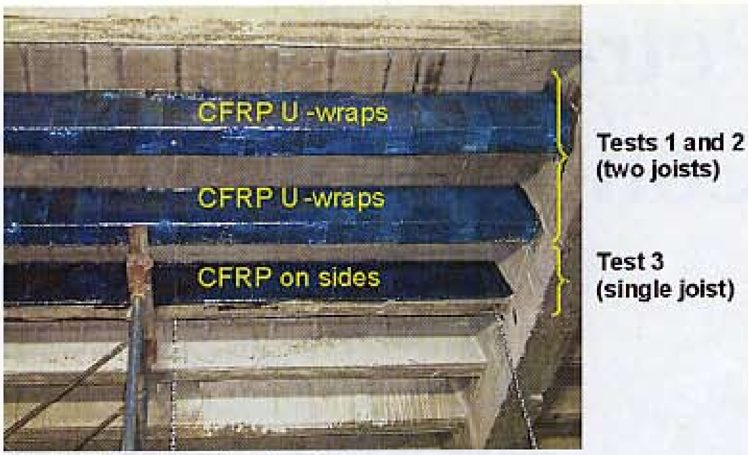

Fig. 5: Shear strengthening of joists

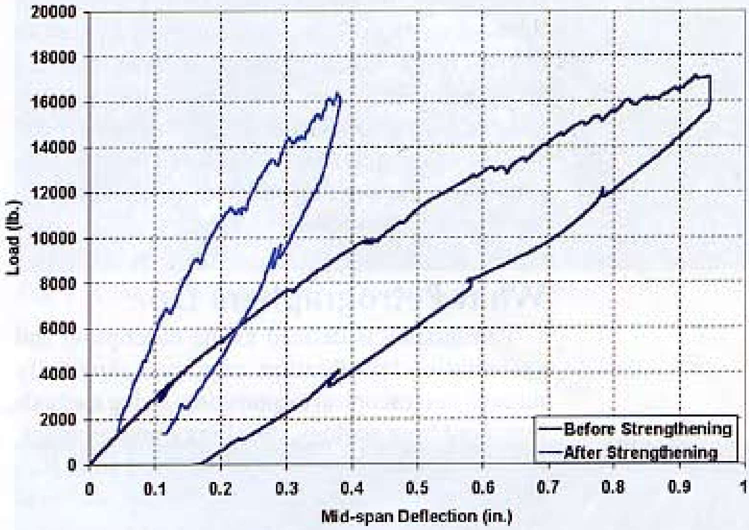

Fig. 6: Comparison of single-T deflection before and after strengthening

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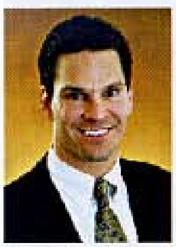

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