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GUIDELINES FOR RAPID LOAD TESTING OF CONCRETE STRUCTURAL MEMBERS

by

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EXECUTIVE SUMMARY

This document describes the protocol for the in situ rapid load testing of concrete structures and presents case studies that illustrate its execution and results. It is meant as a guide for engineers interested in assessment and load testing of structures. The motivation for considering the use of a rapid load test is twofold:

- Technological advances in equipment and instrumentation is allowing structural engineers to safely and economically determine the adequacy of members to resist given load conditions.
- Implementation of new construction and strengthening technologies can gain acceptance if verified by proof testing.

The key feature of a rapid load test conducted with hydraulic jacks is in the ability to progressively expose a structural member to loading-unloading cycles. This allows the engineer the opportunity to maintain a strict control on safety and, at the same time, determine response parameters that are key to structural assessment, namely: linearity of behavior, repeatability of response, and permanency of deformation.

In a rapid load test, loads applied to strategic locations are meant to induce the internal forces equivalent to those resulting from distributed loads. The engineer has to be able to analytically interpret this equivalency when establishing the load level to be applied during the in situ test. This implies an understanding of boundary conditions (i.e., fixity), collaboration of adjoining members (i.e., load sharing), and composite action with structural and non-structural components. A rapid load test consists of concentrated loads being applied in a quasi-static manner in at least six load cycles, with each cycle containing several load steps. The initial cycles achieve relatively low levels of load and are used to verify assumptions made in the preliminary analysis and ensure stability of the system.

The duration of a rapid load test can be significantly shorter than the 24-hour period that has been employed with traditional in situ tests. The cyclic nature of the rapid load test is considered a suitable substitute for the 24-hour sustained load. In any event, a rapid load test can last as deemed necessary by the engineer.

The document is subdivided into five chapters and two appendices. The first chapter is an introduction that deals with the topics providing the justification for the use of rapid load testing. The second chapter provides a description of the planning phases for rapid load testing, emphasizing methods of load application as well as equipment and instrumentation used. The third chapter deals with the test procedure and the interpretation of its results. The fourth and fifth chapters offer conclusions and cited references, respectively. The first appendix presents five case studies conducted on members that were subject to rapid, 24-hour sustained, and failure tests, respectively. The second appendix describes commercial case studies of the rapid load test for five different methods of load application.

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CHAPTER 1 GENERAL

1.1 Notation

b = width of the unit strip (in, mm)

C_1 = multiplier to account for contribution of adjacent elements

C_2 = multiplier to account for distributed load versus point load

i = point on the load-deflection envelope with coordinates (P_i, Δ_i)

l_1 = span in the primary direction (in, mm)

l_2 = span in the transverse direction (in, mm)

n = number of equally spaced deflection readings orthogonal to the span of the test member

P_i = test load at point *i* (lbs., N)

P_{max} = maximum load level maintained in a cycle (lbs., N)

P_{min} = minimum load level maintained at the end of a cycle (lbs., N)

P_{ref} = reference test load for calculating deviation from linearity (lbs., N)

P_T = magnitude of a concentrated load (lbs., N)

P_{ult} = ultimate test load carried by the test member (lbs., N)

R = deflection ratio used to calculate support fixity

w_{ct} = critical uniformly distributed load to be simulated (lbs./ft^2, kN/m^2)

w_d = uniformly distributed dead load (lbs./ft^2, kN/m^2)

w_{ip} = uniformly distributed load in place at time of testing (lbs./ft^2, kN/m^2)

w_l = uniformly distributed live load (lbs./ft^2, kN/m^2)

w_{sim} = uniformly distributed load simulated by a test load (lbs./ft^2, kN/m^2)

a_i = slope of the secant line for step *i* of the rapid load test (lbs./in., N/mm)

a_{ref} = slope of the reference secant line in the rapid load test (lbs./in., N/mm)

D_1 = deflection measured under the load (in., mm)

D_i = deflection under the load at point *i* (in., mm)

D_{ref} = reference deflection for calculating deviation from linearity (in., mm)

$?^A_{max}$ = maximum deflection in Cycle A under a load of P_{max} (in., mm)

$?^B_{max}$ = maximum deflection in Cycle B under a load of P_{max} (in., mm)

$?^A_r$ = residual deflection after Cycle A under a load of P_{min} (in., mm)

$?^B_r$ = residual deflection after Cycle B under a load of P_{min} (in., mm)

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1.2 Scope

The intent of these guidelines is to provide engineering professionals with a method of efficiently and accurately assessing, in situ, the structural adequacy of reinforced and prestressed concrete building components. These guidelines allow the engineer to conclusively determine whether a specific portion of a structure has the necessary capacity to adequately resist a given loading condition. These guidelines establish a protocol for full-scale, in situ load testing including planning, executing, and evaluating a testing program, which will assist the engineer in implementing an efficient load test.

1.3 General Concepts and Objectives

Valuable information regarding the health and performance of an existing structure may be gained by simply measuring its response to load. Traditionally this view has been adopted in the implementation of load tests and structural monitoring. Both of these practices provide evaluations of structures that are much more representative than analytical approaches, especially when little is known about the structure's geometry and composition. Often, however, much is known about the structure with doubts only about certain aspects or characteristics. In these circumstances, a load test would provide valuable information. However, it is difficult to justify the time and expense associated with full-scale load testing. To this end, rapid in situ load testing takes the same approach to loading a structure and measuring its response, but the loads and measurements are specifically designed to reveal a certain characteristic of the structure. This approach allows for a much simpler evaluation that can be carried out in a fraction of the time and at a much lower cost.

Central to the concept of rapid load testing is the identification of the structural component and response that is of interest. For example, it may be of interest to investigate the bending capacity of a flat slab at mid-span of the column strip. The rapid load test would involve applying concentrated loads to the slab through the use of hydraulic jacks. The location and magnitude of these loads is carefully chosen to produce critical responses in the structure while limiting the potential for causing permanent damage. The induced deflections and strains are measured, and the structure's performance is evaluated based on its response to loading.

1.4 Background Information

Load testing has long been a viable option for investigating a building which exhibits "reason to question its safety for the intended occupancy or use" (Building Officials and Code Administrators International, 1987). Reports of full-scale in situ load tests on buildings in the United States date back as far as 1910 (FitzSimons and Longinow, 1975). Committee 318 of the American Concrete Institute (ACI 318, 1956) has understood the need for guidelines for load testing of reinforced concrete (RC) structures for many years. Researchers (Genel, 1955a; Genel, 1955b; Bares and FitzSimons, 1975; FitzSimons and Longinow, 1975; RILEM Technical Committee 20-TBS, 1984; Hall and Tsai, 1988; Bungey, 1989; Fling, et al., 1996, Gold and Nanni, 1998; Nanni and Gold, 1998a; and Nanni and Gold, 1998b) have investigated and discussed the methods of applying test loads and measuring structural response parameters. These investigations have attempted to refine the testing procedure over the years, but the fundamental protocol remains unchanged. Baseline measurements of the structural response parameters are taken before any loads are placed on the member. The structure is then loaded to a certain level and measurements are again recorded. Based on the measured response to loading, various acceptance criteria exist for determining the outcome of an in situ load test. Most existing criteria are only applicable to elements tested in flexure (Bungey, 1989 and ACI Committee 318, 1995).

Currently, load testing protocols are included in various standards and specifications within the construction industry. The requirements of the ACI 318 Building Code (1995) include provisions for static load testing of concrete structures. The general procedure required by ACI 318 involves gradually applying the test load until a maximum load is reached and maintaining that load for 24 hours. Measurements are recorded before any test load is applied, at the point at which the maximum load is achieved, after 24 hours of constant loading, and 24 hours subsequent to the removal of the test load. The structure is evaluated based on the maximum recorded deflection and the amount of deflection recovery.

In recent years, attempts have been made to change the way in which in situ load tests are conducted. Some modifications to the load testing procedure defined in Chapter 20 of the ACI 318 Building Code (1971) were suggested by a subcommittee formed within ACI Committee 437 (1990). One of those changes dealt with the duration of load application and time intervals between response measurements. It was proposed that the maximum test load need be applied for only 12 hours with the final measurements taken 12 hours after the load has been removed. However, there is still no physical basis for either the 24-hour or the 12-hour duration of load application. Long-term effects in concrete structures, such as creep, do not occur in a matter of hours or days. Rather, these effects only become significant after one month of constant load application (ACI Committee 318, 1995).

Recognizing that the long-term effects are not developed, the rapid load testing procedure shortens the duration of the load application to a matter of minutes. Loads are applied in quasi-static load cycles and the response of the structure is continually recorded. The rapid load testing procedure was originally developed to offer a non-destructive yet conclusive demonstration of the performance of new construction techniques and technologies. Among the first applications of the rapid load testing technique was the proof testing of externally bonded fiber reinforced polymer (FRP) sheets to strengthen concrete floor systems. In this application, much is known about the existing concrete structure. However, the novelty of the FRP system is a cause for concern. Rapid load testing may be used to demonstrate the performance of the FRP systems in situ. Since the load test provides easy-to-understand physical results, the test is able to eliminate doubts about the FRP system's performance and provides the engineer and owner involved with the project an added degree of confidence.

This document will detail a protocol for establishing the duration of load application, the modality of the load cycles, and the criteria for rating the outcome of a rapid load test. The evaluation criteria are based on parameters that can be generalized for different types of load tests. Also, such parameters can be computed during the execution of the test, providing the means for real-time evaluation. Long-term effects that deal with the durability of concrete or other materials should be investigated using methods other than those proposed in this document.

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CHAPTER 2 PLANNING A RAPID LOAD TEST

A successful load test provides information essential to the assessment of the structural condition of the tested member. There are several phases involved in carrying out a successful load test. Information about the existing structure must first be gathered, the method of load testing must be determined, the load test must be carried out, and finally the results of the test must be analyzed and interpreted.

2.1 Evaluation of the Structure

The preliminary steps in the planning of a load test are independent of the test type. These steps, clearly defined by ACI Committee 437 (1991) and the American Society of Civil Engineers (1991), include a study of drawings, reports, and calculations, verified by an on-site inspection, as well as determining the loading history and material characteristics of the structure.

2.1.1 Preliminary Investigation

Before testing a given structure, a firm understanding of what is and is not known about the structure is required.

- Structural Geometry: On-site inspections usually include the verification of dimensions and placement of reinforcement as shown on the as-built drawings, discussed in reports, and used in calculations by the designer.
- Loading History: Knowledge of the loading history may play a key role in assessing the structure’s state. If damage has occurred, a study could reveal overloading or design and/or construction errors. If the use of a structure is changed, original and new load requirements must be determined.
- Material Characteristics: Material properties, such as concrete compressive strength and reinforcing steel grade may have to be determined from samples collected in situ.

2.1.2 Definition of Objectives

Rapid load tests can be run to determine the reserve capacity in a member that will undergo a change in usage or to quantify the level of damage in a member due to deterioration or other causes. They may also be used to establish the service levels of a unique design or verify the functionality of novel materials. Questions about a member’s capacity due to design or construction flaws may be answered through rapid load testing as well. The objectives of a rapid load test should address two issues:

- Critical loading condition(s): The rapid load test is intended to simulate the critical loading condition. For a meaningful evaluation of the structure, the critical loading condition is recommended to be at least 85% of its factored design loads minus the loads in place at the time of testing (e.g., self-weight). The critical loading condition for a given structure will depend on its intended use and design. As an example, using the load factors given by ACI Committee 318 (1995), the critical loading condition for a structure resisting uniformly distributed dead and live loads can be found from Equation 2.1.

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$$w_{ct} = 0.85(1.4w_d + 1.7w_l) - w_{ip}$$ **Equation 2.1**

The quantities shown in Equation 2.1 are defined as follows:

w_{ct} = critical uniformly distributed loading condition to be simulated

w_d = uniformly distributed dead load

w_l = uniformly distributed live load

w_{ip} = uniformly distributed load in place at time of testing

- Critical response(s): The load test is meant to simulate selected responses induced by the critical loading condition. For example, the load test may induce the same bending moment at mid-span of a beam that the critical loading condition would induce. It is, therefore, necessary to determine what critical responses are of interest and need to be induced.

2.2 Test Planning

Based on the objectives, a test plan should be developed that outlines the method of load application, the magnitude of the loads to be applied, and the measurements that will be taken during loading. This plan should reflect careful design and analysis performed by a qualified engineer. Guidance on the planning of these various aspects is given in the following sections.

2.2.1 Selection of Members

When considering a large population of members within a structure, the members tested should be representative of the structure in question. The most critical geometries for the most critical load cases should be represented in the selected member. For structures with repeated elements, it may be necessary to test a number of representative elements to arrive at a meaningful statistical conclusion as to the performance of the untested members. The engineer’s judgement is critical to the proper selection of the type and number of elements to be tested.

Consideration must also be given to safety when selecting a test member. In certain instances, isolation of a member results in more predictable behavior of a system and ensures little damage to the rest of the structure. When the stiffness of adjacent elements adds significantly to the stiffness of the tested element, isolation may be very effective in lowering the maximum test load and reducing the chances of an alternate mode of structural failure.

2.2.2 Methods of Load Application

The ideal load test would involve applying loads that exactly replicate the design load conditions. In this way, the resulting response of the structure is exactly as it would be under said loading. This is not always achievable, however. In the case of a floor or roof system, design loads are typically a uniform downward pressure. While this condition could be replicated by flooding the surface with water or stacking weights, such procedures are complicated and time consuming. And more importantly, the load magnitude cannot be easily varied. Conversely, a rapid load test is based on the application of concentrated loads by means of hydraulic jacks. This method allows for rapid variation in the magnitude of the test load, which provides the means for cyclic loading of the structure. Consideration, however, should also be given to the fact that the hydraulic jacks used to supply the test load must be provided with an adequate reaction.

Depending on load magnitudes and geometry of the structure, a suitable load application method should be selected. Examples of various types of load application methods (i.e., push-down, pull-down, closed loop, vehicle, and dropped weight) that allow for the load magnitude to be easily varied are compared in Table 2.1 and are described below. The setup time (Table 2.1, Column 2) includes installation of all loading devices and instrumentation used to monitor the structural behavior. These relative times do not take into account any work which may be involved in preparing the members for testing (e.g., removal of finishes, saw-cutting of members, drilling of holes, etc.), because such conditions are unique to a specific test and are independent of the test method. The minimum requirements (Table 2.1, Column 3) are those which are essential to the loading of the test member. More equipment may be required depending on the conditions of the structure. The levels of on-site support (Table 2.1, Column 4) include the activities that should be carried out by an on-site contractor. This includes operating forklifts, preparing test members, assisting in load setup, etc. The relative level of difficulty of load variation (Table 2.1, Column 5) is based on the time it takes to change from one level of load to another. Another requirement for each test method is shown as the source of the reaction (Table 2.1, Column 6). For each test method, the structural member used to provide the reaction must be carefully checked. These load application methods have limitations (Table 2.1, Column 7) that should be considered.

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Table 2.1: Summary of load testing methods

Test Method (1)	Setup time (2)	Minimum loading requirements (3)	On-site support (4)	Load variation (5)	Source of reaction (6)	Limitations (7)
Push-down	Medium	-Hydraulic jack and pump -Extensions to ceiling -Shoring of above floor(s) -Adequate weight of floors above for reaction	Little to None	Easy	Shored floor(s) above test member	Requires floor(s) above for reaction
Pull-down (fixed reaction)	Medium	-Hydraulic jack and pump -Hole in member -High strength rod, chain, or cable -High strength pulley -Adequate source of reaction	Little to None	Easy	Columns or piles below test member	Requires symmetric and close reaction points
Pull-down (mobile reaction)	Medium	-Hydraulic jack and pump -Hole in member -High strength rod, chain, or cable -Forklift or other mobile source of reaction	High to Medium	Easy	Dead weight below test member	Maximum test load must be relatively low
Closed loop	Long	-Two hydraulic jacks and pump -Two holes in member -High strength rod, chain, or cable -Source of reaction between test members -Adequately sized reaction beam	High	Easy	Internal structural member between tested members	Location and magnitude of load dependent upon size and length of reaction beam
Vehicle	Short	-Forklift or other vehicle capable of carrying different amounts of load -Various amounts of weight	High to Medium	Difficult	Not Applicable	Load variation is time consuming
Dropped Weight	Short	-Forklift or other device to carry load -Various amounts of weights	High to Medium	Difficult	Not Applicable	Load variation is time consuming

- Push-down test: In the push-down test, one or more hydraulic jacks with extensions are used to provide the load that results in downward concentrated forces on the test member. Figure 2.1 shows an overall schematic of the push-down test method. In this figure, the darkly shaded member is undergoing the load test in positive flexure. The extensions, attached to the hydraulic jacks will react against the ceiling when the jacks extend. Shoring is installed on one or more floors above the tested member to share the reaction. The displacement transducers mounted on tripods below the test member are used to measure the deflection at several points along the span of the member. Figure 2.2 shows a detail of the loading devices used in the push-down test method. Again, the darkly shaded member is undergoing the load test. The plywood shown in this figure is used to protect the concrete from any localized damage. Also shown in Figure 2.2 is the hydraulic jack and the extensions used to apply the test loads. The extension cap is used as a centering device for the load cell. This test method has been used to verify the positive and negative flexural strengthening of prestressed and post-tensioned flat slabs and to determine the shear capacity of RC ceiling joists. For additional information regarding members tested using the push-down method, see Appendices A and B in this document, Gold and Nanni (1998), Nanni and Gold (1998a), Nanni and Gold (1998b), and Nanni, et al. (1998).

- Pull-down test (fixed reaction): In the pull-down test with a fixed reaction, the reaction is provided below the tested member. Figure 2.3 shows an overall schematic of the pull-down test method using a fixed reaction. The darkly shaded member is undergoing a load test in positive flexure. The hydraulic jack, shown in this figure, applies the test load on the darkly shaded member with the reaction provided by the two columns. The displacement transducers, mounted on tripods on the floor below the test member, record the member's deflection at several locations. Figure 2.4 shows a detail of the loading equipment in the pull-down test method. The high-strength steel bar is attached to the hydraulic jack and passed through the tested member. At the end of the high-strength steel bar is a pulley, over which a chain passes. The chain is wrapped around columns on the floor below the tested member. Fire hoses were wrapped around the column in this case in order to protect them from any localized damage. As the hydraulic jack extends, the high-strength steel bar pulls up on the chain, which reacts against the columns resulting in a downward concentrated load applied to the darkly shaded test member. Plywood is used to protect the concrete from any localized damage. The load cell measures the amount of load applied to the member during the test. This method has been used to verify the strengthening of an RC slab. For additional information regarding members tested using the pull-down method with a fixed reaction, see Appendix B in this document.

- Pull-down test (mobile reaction): In the pull-down test with a mobile reaction, the reaction is again provided below the tested member. Figure 2.5 shows an overall schematic of the pull-down test method using a mobile reaction. This figure is the view parallel to the span of the test member. The darkly shaded roof member is undergoing a load test in positive flexure. Shown on this figure is the hydraulic jack, which provides the test load to the member by using the weight of the forklift as a reaction. The hydraulic jack is connected to a chain, which passes through the test member and is attached to a spreader beam. The displacement transducers are mounted on tripods and record the deflection of the member at several points along the span of the test member. Figure 2.6 is a detail of the loading equipment used in the pull-down test method with a mobile reaction. This figure is the view perpendicular to the span of the test member. The hydraulic jack, while extending, pulls down on the chain and subsequently the spreader beam. The spreader beam sits on plywood in order to protect the concrete from any localized damage. Again, the weight of the forklift is used as a reaction and the load cell is used to measure the applied load. This method has been used to verify the strengthening of a prestressed concrete (PC) shell. For more information regarding members tested using the pull-down method with a mobile reaction, see Appendix B in this document, Barboni, et al. (1997), and Benedetti and Nanni (1998).

- Closed loop: The closed loop test is the most elegant of all the choices because no external reaction is required. As shown in Figure 2.7, the closed loop method is ideal for testing two members simultaneously if the locations of the loads are reasonably close. Shown in this figure are two hydraulic jacks, which apply the load to the two darkly shaded test members. The inverted tee beam, located between the two test members, supplies the reaction. The displacement transducers measure the deflection at several points along the spans of both beams and they are located below the test members. Figure 2.8 shows a detail of the loading devices in the closed loop method. As the hydraulic jacks extend, they pull on the high-strength steel bars, which lifts the reaction beam below the test members. Once the reaction beam comes into contact with the inverted tee beam, the resulting load is a downward force under each hydraulic jack. The plywood under the hydraulic jacks and between the inverted tee and the reaction beam are used to protect the concrete from any localized damage. The load cell measures the amount of load applied to one of the test members throughout the test. One requirement of this test method is that one pump must operate both hydraulic jacks in order to ensure equal loads at each jack. Figure 2.9 is a view of the closed loop method perpendicular to the span of the beam in order to show how the concentrated load under each jack can be applied to the two stems of a double tee through the use of a steel section. The steel section sits on plywood above the stem of the double tee in order to protect the concrete from any localized damage. This method has been used to verify the strengthening of PC double tee beams and PC joists in parking facilities. For more information about members tested using the closed loop method, see Appendix B in this document, Sawyer (1998), Hogue, et al. (1999a), Hogue, et al. (1999b), Mettemeyer, et al. (1999), Wuerthele (1999), and Gold, et al. (2000).

- Vehicle: Figure 2.10 shows how a loaded forklift is used to apply load on the darkly shaded test member. The displacement transducers, mounted on tripods and located below the test member, record the deflection at several locations during the load test. The forklift, carrying a designated amount of weight, stops at several predetermined locations on the test member so that response measurements can be taken. Figure 2.11 shows a plan view of the forklift with the heavy axle centered on the test member. The displayed locations of the displacement transducers are that of a typical two-way system. This method has been used to verify the strengthening of PC decks in a power plant and a pier. For more information, see Appendix B in this document and Bick (1998).

- Dropped Weight: Figure 2.12 shows how a load test may be run by intentionally dropping a known amount of weight, from a given height, in a designated location and recording the structural response. The displacement transducers, which record the deflection of the member at several points, are located below the darkly shaded test member. Figure 2.13 shows a plan view of the forklift dropping the test load in the designated location. The positions of the displacement transducers may be those used if the test member is a two-way slab. The dropped weight test method has been used to verify the strengthening of a PC beam. For more information, see Appendix B in this document.

2.2.3 Test Load Magnitude

The magnitude of the test load is a function of the internal forces that need to be generated at the critical cross-section. As an example, a concentrated test load can be used to reproduce the same bending moments in a unit width of a slab as a uniformly distributed design load. The magnitude of the concentrated load to accomplish this must be determined through careful structural analysis. The analysis to determine the test load magnitude should consider the following factors:

- <u>Load Pattern:</u> The difference between the test load pattern and the pattern of the critical load condition should be considered. This is typically the difference between applying concentrated loads versus applying a uniformly distributed load.

- <u>Load Sharing:</u> Often, test loads are not applied to adjoining elements that are loaded by the critical loading condition. These adjoining elements (structural or non-structural) may contribute to the stiffness of the member being tested and share load with the tested member. Load sharing would include the stiffness of the elements in the orthogonal direction (e.g., two-way action in slabs). These effects must be considered in the analysis, which often precludes the use of simple one-dimensional structural models. Due to load sharing effects, two- or three-dimensional modeling is typically required. Alternately, the member being tested may be physically isolated from adjacent elements. Figure 2.14 shows a double tee beam that has been isolated from the adjoining tees by saw cutting along each joint. By isolating the double tee in this fashion, the effects of load sharing are prevented and do not need to be considered in the analysis.

- <u>Boundary Conditions:</u> The boundary conditions of the test member play an important role in determining the internal force distribution. Initial assumptions need to be made with regard to the degree of fixity of the supports. The degree of fixity can be correlated to a spring constant to be used in an analytical model (simple support, 0% fixity and a fixed end, 100% fixity). An estimation of the actual support fixity can be made after the structure has been loaded and the measurements of its deflection recorded. Guidance on this post-testing analysis is given in Section 3.3.1.

- <u>Composite Action:</u> Often, composite action (e.g. topping slabs) is not relied upon in determining responses induced by the critical load condition even though such action does exist in situ. The test load magnitude may need to be adjusted to or the composite action be removed prior to the load test.

- <u>Temperature and Environmental Effects:</u> Variations in temperature and environmental conditions during testing may alter the monitored responses. Instruments need to be adjusted or the variations need to be avoided.

Once the magnitude and location of the maximum test load and the method of load application have been established, the strength of the element being tested with respect to other forces must be checked to ensure safety. For example, if a test is meant to produce a critical flexural response, the shear capacity of the structure should be checked to prevent shear failure. If members within the structure are used to supply the reaction to the test load, the capacity of those members should be checked as well.

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It is important to recognize that any structural analysis must treat fixity and stiffness as assumptions. The preliminary structural analysis is used to estimate the magnitude of the test load only. Once the structure is loaded and its response is measured, the assumptions made in the analysis can be refined based on the structure's actual behavior. With these refinements, the actual induced internal forces can be determined with a much higher degree of accuracy. Guidance on refining the analytical model is given in Section 3.3.1.

2.2.4 Prediction of Structural Responses

The preliminary analysis of the structure should also be used to predict the deformations of the structure to be measured in the field. Deformations under various load levels should be predicted in order to compare the deformations at various stages of loading during the load test. These predicted deformations allow the individual performing the test to determine if the member is behaving as expected. Predicted deformations of concrete members are only used as approximations since the changing moment of inertia along the length of the test member makes exact calculations difficult. However, if the predicted deformations are substantially different from the actual deformations, then the load test can be stopped before any damage is done to the member. Further analysis may need to be performed to resolve the discrepancies.

2.3 Equipment

Advances in technology in the area of load application and structural response measurements have provided the means for this rapid load testing procedure. The following sections discuss some of the equipment that has been used to perform rapid load tests.

2.3.1 Hydraulic Jacks and Pump

The equipment that has made rapid load testing possible is that which supplies the test load. Hydraulic jacks are used in rapid load testing because they are easy to install and control. Hydraulic jacks allow for relatively rapid variations in load, but the greatest advantage they have over using dead weights (e.g., water, bricks, etc.) is that the load applied by the hydraulic jacks can be removed instantaneously if a problem should arise during a load test. Figure 2.15 shows two 60,000-lbs. (267 kN) hydraulic jacks. These jacks, including the steel bases, only weigh about 35 lbs. (156 N). Hydraulic jacks with a variety of capacities are available. The pump, which supplies the fluid to the hydraulic jacks, can either be electrical, as shown in Figure 2.16, or manual, as shown in Figure 2.17. For an electric pump (Figure 2.16), the pressure regulator is used to control the amount of hydraulic fluid flowing to the jacks, which provides a controlled means of load application. An electric pump usually has a control switch, which can be used for immediate removal of the applied load. For convenience, the electrical pump may be stored in a transport box as shown in Figure 2.18. The transport box, supported on wheels, may be used to move the hydraulic jacks and hoses, in addition to the pump, to the test site.

2.3.2 Instrumentation

Some of the instrumentation used to monitor the behavior of a test member is summarized in Table 2.2. This table includes the common names for the devices, some of their suggested uses, recommended minimum measurable values, and measuring ranges. Additional information on these devices as well as many others is available in literature (Bungey, 1989; Carr, 1993; and Fraden, 1993).

Table 2.2: Summary of instrumentation used in rapid load testing

Parameter	Devices	Recommended Minimum Measurable Value	Measuring Range
Deflection	LVDT	0.0001 in.	± 2 in.
Rotation	Inclinometer	0.001 deg.	± 3 deg.
Strain	Strain Gage	1 με	±3000 με
	Extensometer	50 με	±10,000 με
	LVDT	50 με	±10,000 με
Crack Width	Extensometer	0.0001 in.	±0.2 in.
Load	Load Cell	10 lbs.	0 - 200,000 lbs.
	Pressure Transducer	100 lbs.	0 - 200,000 lbs.

(1 in. = 25.4 mm, 1 lb. = 4.45 N)

Deflections are measured using linear variable differential transducers (LVDT), shown in Figure 2.19. LVDTs are available in a variety of ranges and accuracy levels. In order to reach test members, LVDTs are often mounted on tripods and/or placed on scaffolding. LVDTs used in rapid load testing should have a spring-loaded inner core, which allows the measuring head to return to some reference position.

Inclinometers, shown in Figure 2.20, are used to measure the rotation or slope of a test member. Because values of slope can easily be correlated to deflections, these instruments can be essential when testing a member that is too tall for LVDT stands to reach. The inclinometer shown in this figure can be mounted on a variety of vertical and horizontal surfaces.

Strains in a test member can be measured in a variety of ways, depending on the level of accuracy and the expected magnitude. The most common method for measuring strain is through the use of electrical resistance strain gages, which are bonded directly to the surface of the material for which the strain will be measured. Figure 2.21 shows two electrical resistance strain gages used to read the compression strain in concrete. Strain gages can also be mounted on steel or other materials, which are expected to undergo tensile forces. Because they are susceptible to variations in temperature, most electrical resistance strain gages have temperature compensation coefficients. Electrical resistance strain gages are ineffective when they are intersected by a crack. To measure the strain over a crack, extensometers or LVDTs can be used. An extensometer, as shown in Figure 2.22, is attached directly to the surface on two knife-edges, which straddle an anticipated or existing crack. An extensometer can then be used to either measure the average strain over the gage length between the two knife-edges or measure the change in width of an intersecting crack. LVDTs can be used to determine the average strain over a larger gage length than that provided by the extensometer. Figure 2.23 shows how an

LVDT can be used to measure strain. The horizontal LVDT is placed into a bracket, which is fixed to the test member. Another bracket is fixed to the test member such that the apparatus spans an existing or an anticipated location of a crack. The distance between the two brackets is the gage length over which the average strain is computed.

A device used to monitor the level of load application is a load cell, shown in Figure 2.24. As a requirement of many of the load testing methods described above, this load cell is donut shaped so that a high-strength steel bar may be passed through it. Load cells come in a variety of shapes, sizes, and capacities. Another advantage to the use of hydraulic jacks is an additional means of monitoring the load they apply. Pressure transducers can be used to measure fluid pressures in the hydraulic system, which can be calibrated to a specific level of load.

A data acquisition system, as shown in Figure 2.25, which is capable of collecting readings from several devices simultaneously as load is being applied, is essential to the performance of a successful rapid load test. The data acquisition system, shown in this figure, is capable of simultaneously collecting data from 24 separate devices, including pressure transducers, load cells, LVDTs, inclinometers, extensometers, and strain gages. The data acquisition unit is connected to a laptop computer, in which all the collected data is stored. The data acquisition system, much like the electric pump, is stored in an easy to handle transport box, which is taken directly to the test site. The transport box, mounted on wheels for ease in handling, is also equipped with additional storage compartments, in which the measuring devices can be stored.

2.4 Execution

Not until a sufficient amount of planning has been done can the rapid load test proceed. All parties involved should be aware of the levels of load to which the member will be tested, and there should be a clear understanding of the events that could occur that would lead to the termination of a load test. All information regarding the load test should be clearly defined in a “Plan of Action” that is distributed, in advance, to all the concerned parties. The client or a representative should review the “Plan of Action” carefully and give approval before the load test begins.

A concern in running a load test is the safety of the structure and those persons performing the load test. The use of scaffolding, shoring, straps, or chains may be key in the prevention of collapse of the member if a premature failure should occur. Figure 2.26 shows how scaffolding and timber bracing can be used for emergency support of the dead weight of the test member. A safety measure should in no way interfere with the results of the load test. Only those persons essential to the load testing procedure should be in the area during the load test. Those persons performing the load test should always remain a safe distance from the test member. No individual should walk on or under a member being tested when test loads are being applied. Should it be essential to walk under or on a test specimen, the test load should first be decreased to a load that is deemed safe by the engineer in charge of the load test. Safety is essential to the performance of a successful load test.

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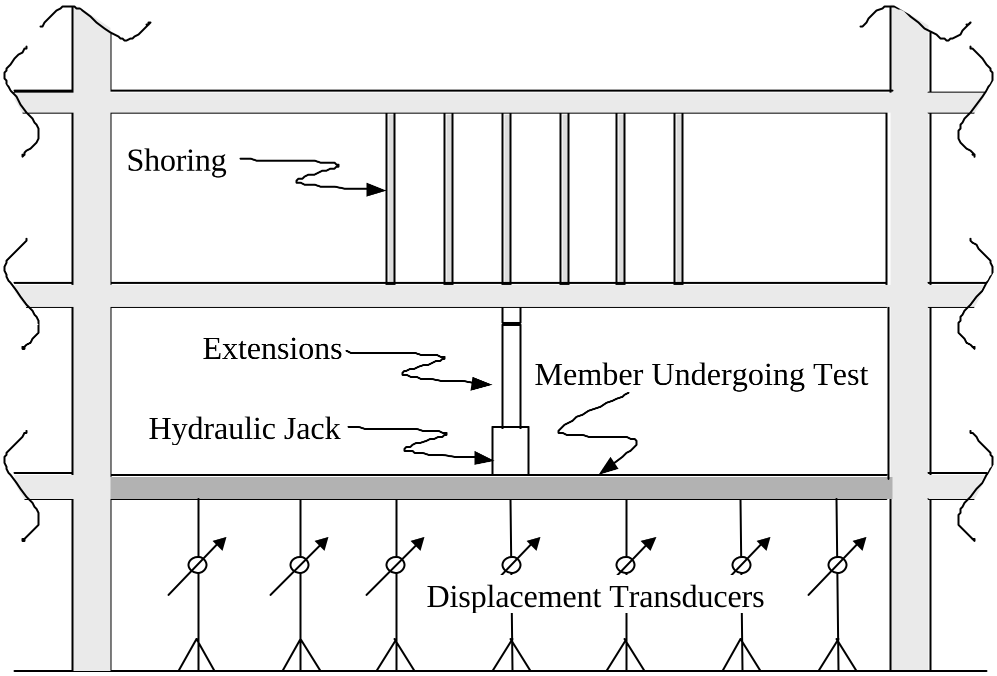

Figure 2.1: Push-down test configuration

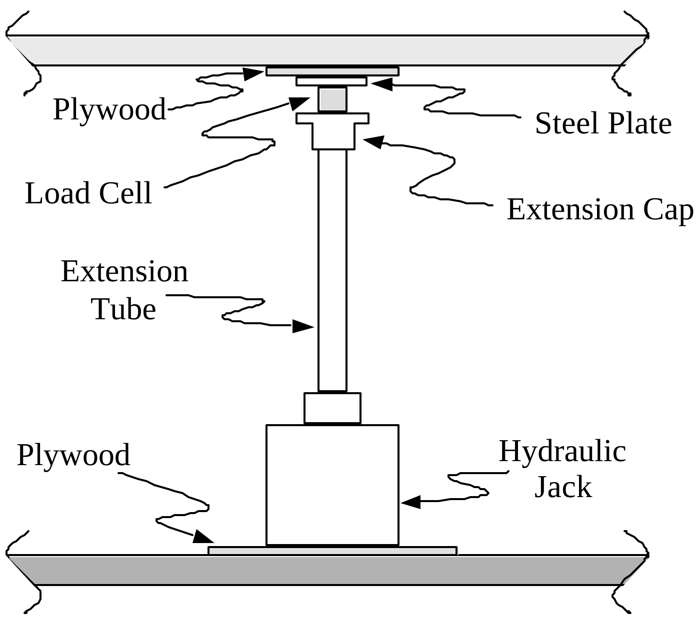

Figure 2.2: Detail of push-down test method

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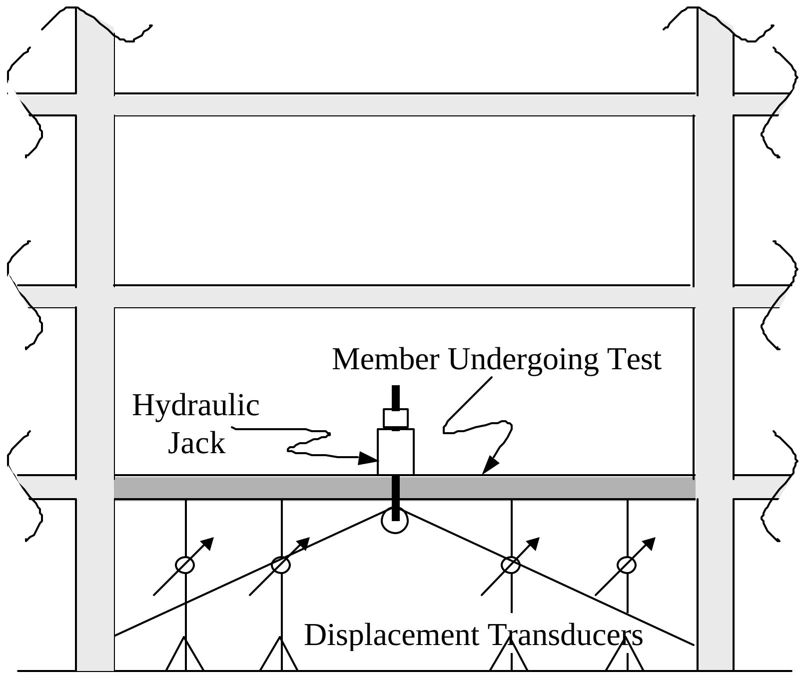

Figure 2.3: Pull-down test configuration with a fixed reaction

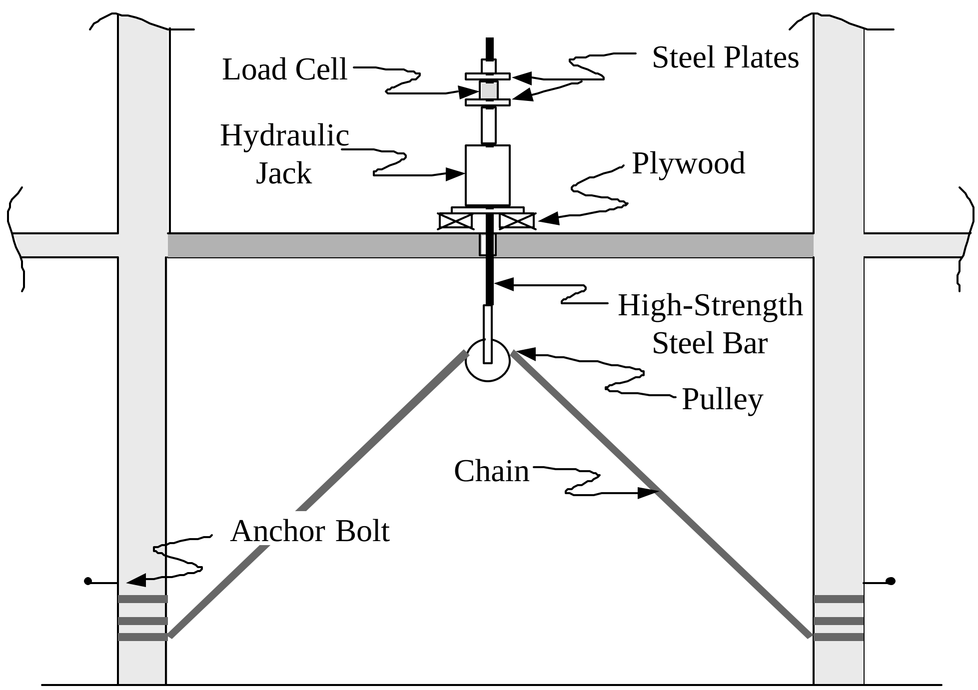

Figure 2.4: Detail of pull-down test method with a fixed reaction

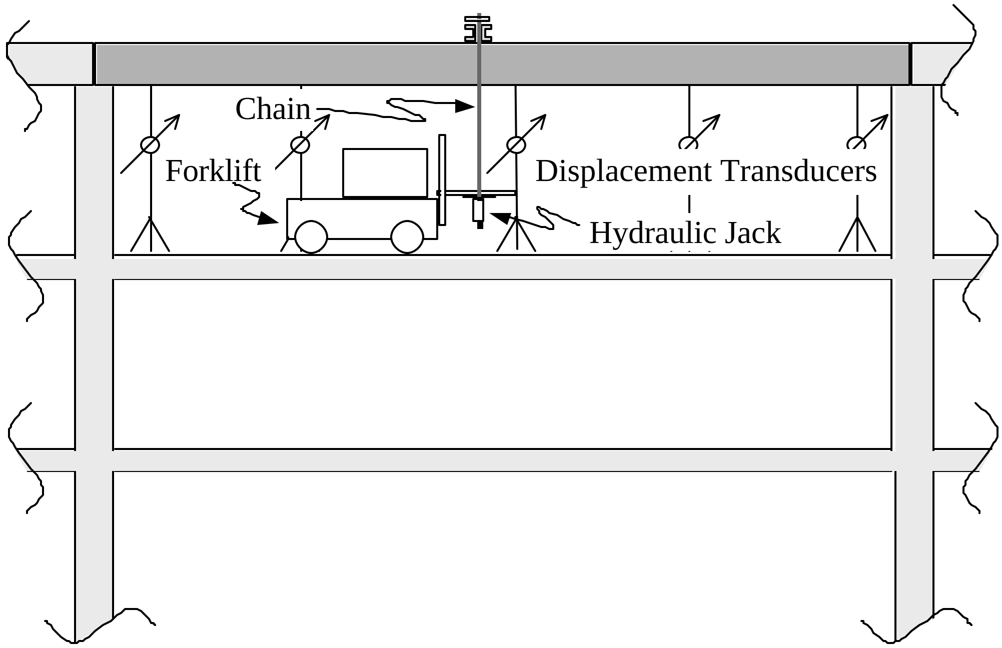

Figure 2.5: Pull-down test configuration with a mobile reaction

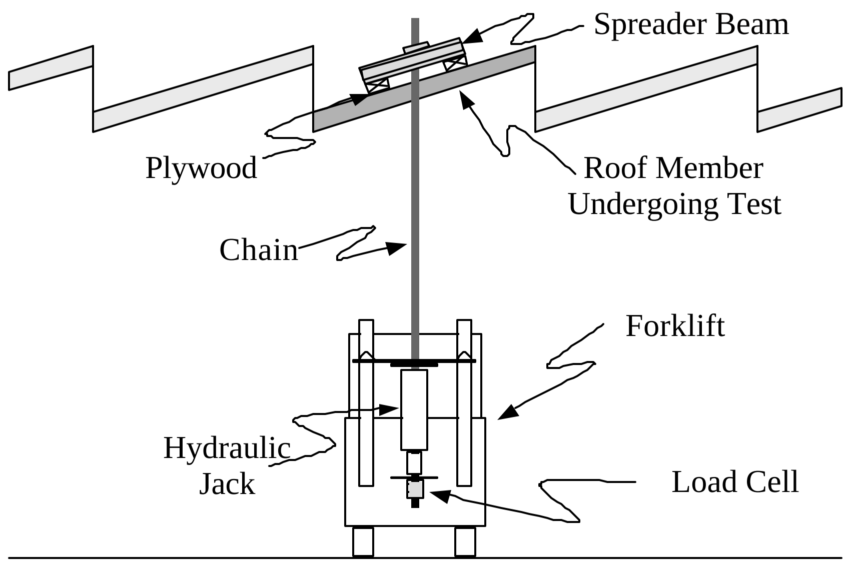

Figure 2.6: Detail of pull-down test method with a mobile reaction

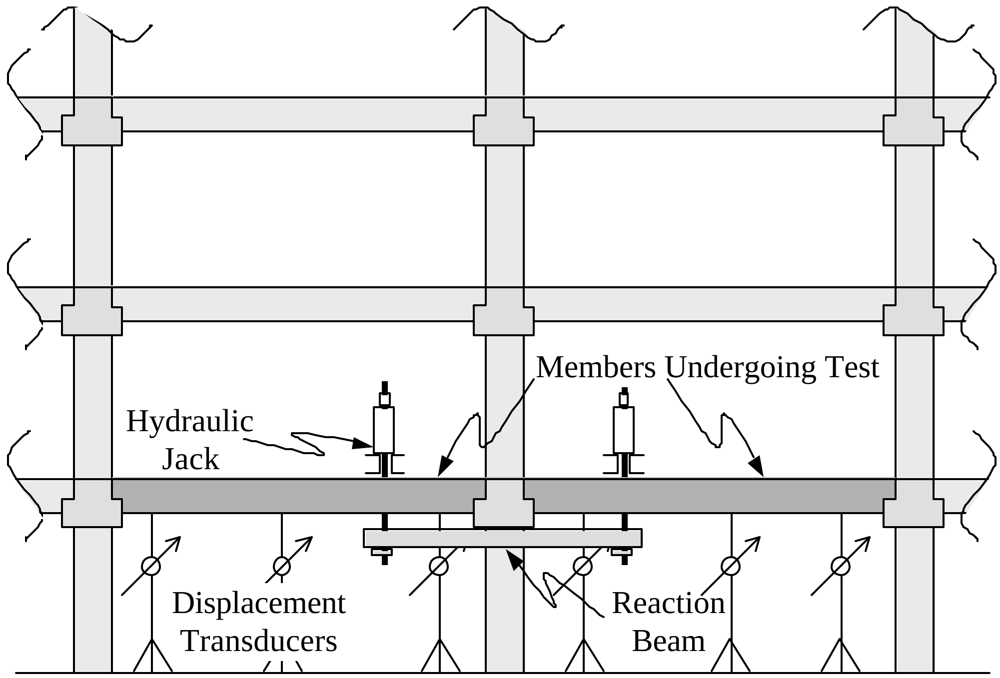

Figure 2.7: Closed loop test configuration

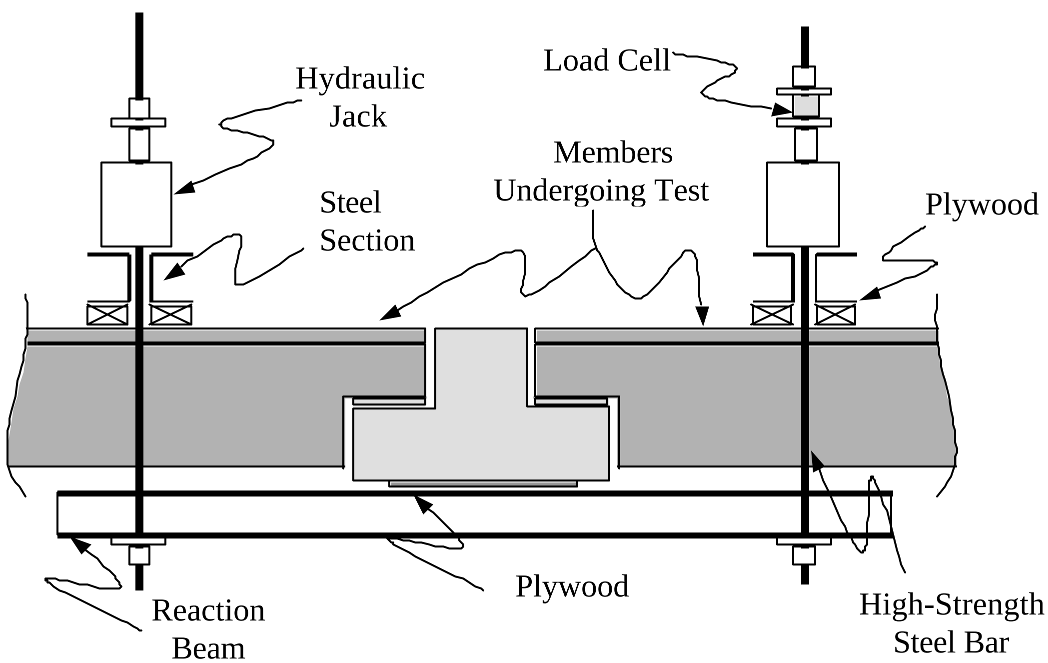

Figure 2.8: Detail of loading devices for the closed loop method

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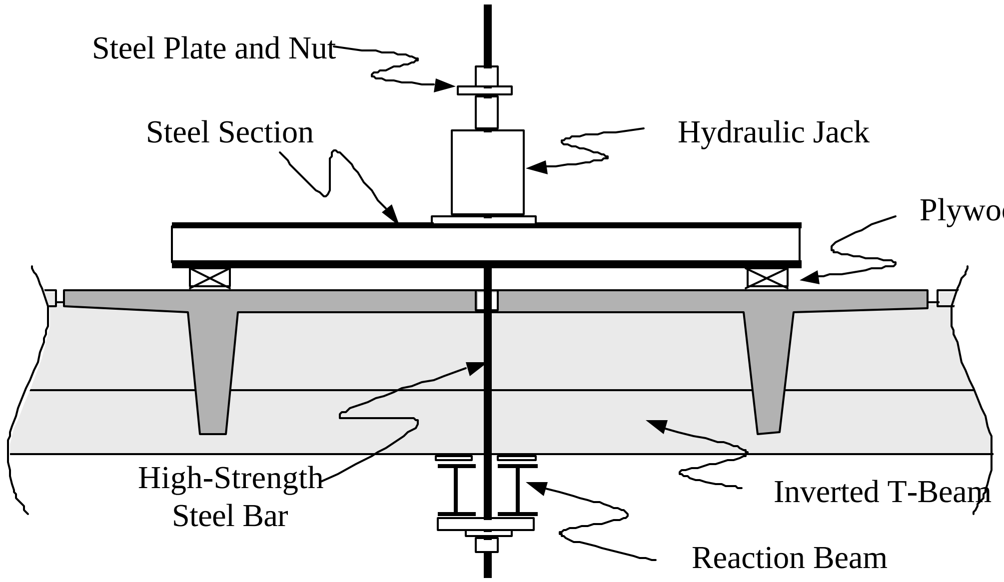

Figure 2.9: The closed loop method can be used to apply loads to both stems of a double tee

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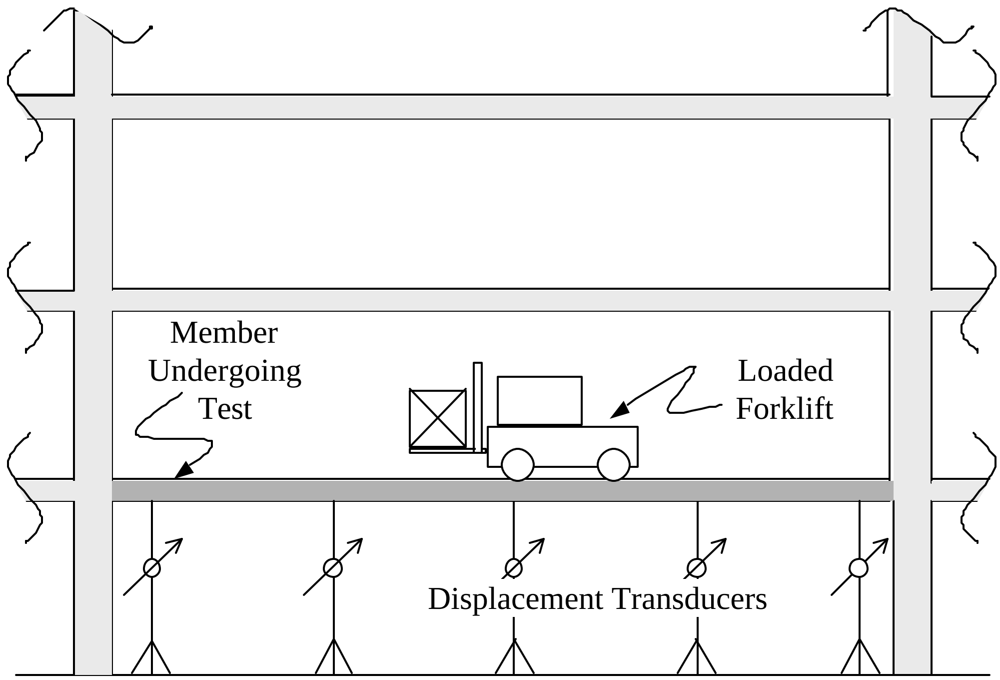

Figure 2.10: Vehicle loaded test configuration

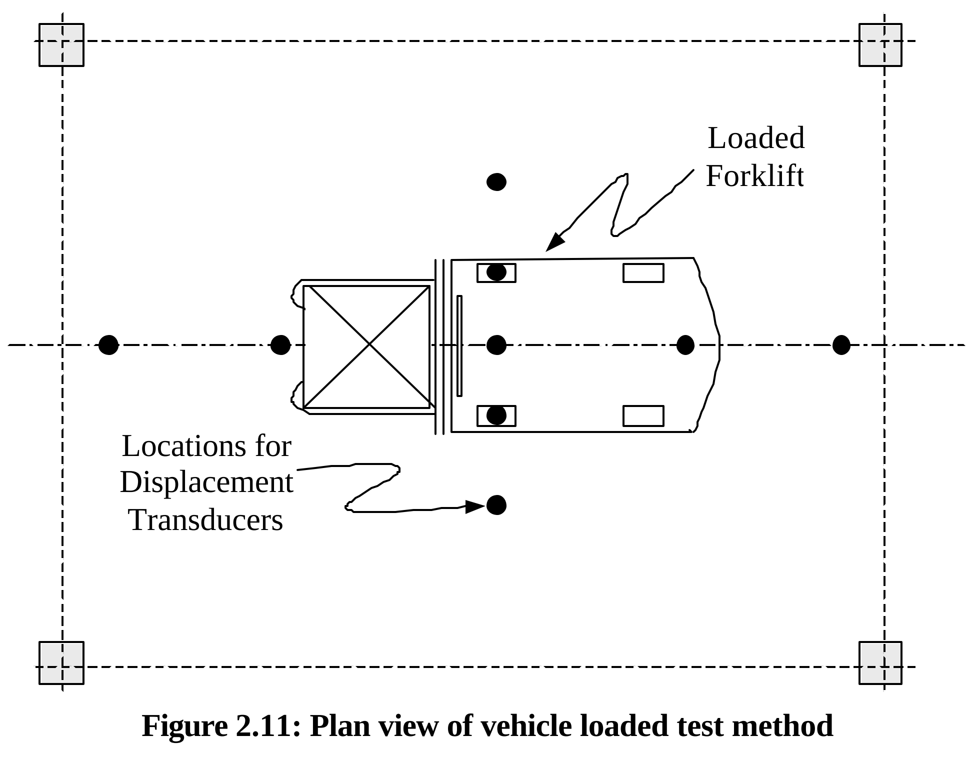

Figure 2.11: Plan view of vehicle loaded test method

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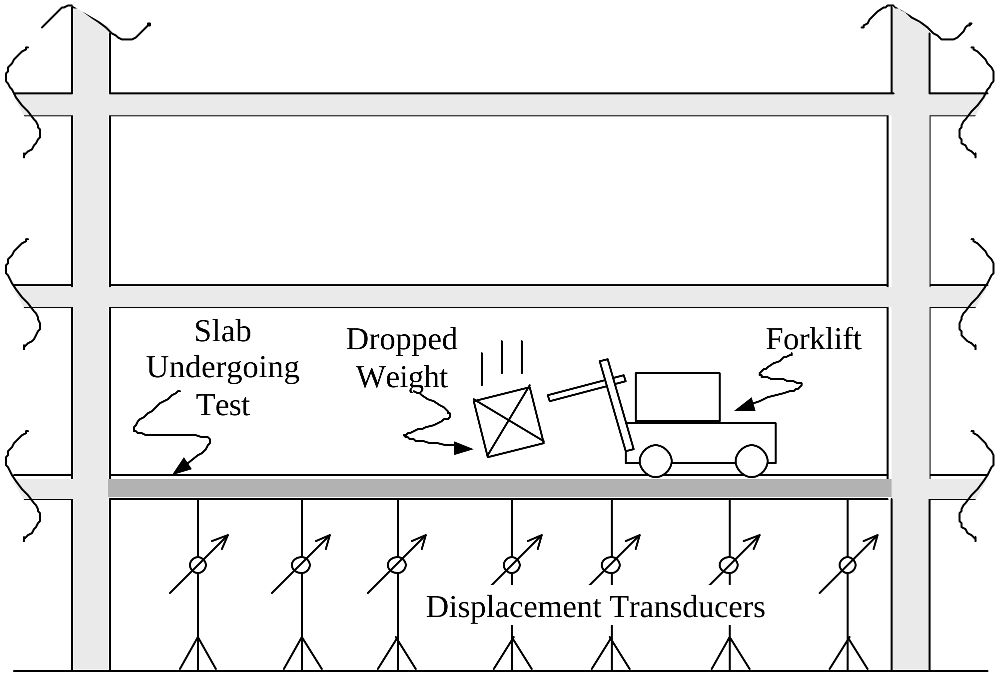

Figure 2.12: Load test configuration for a dropped weight

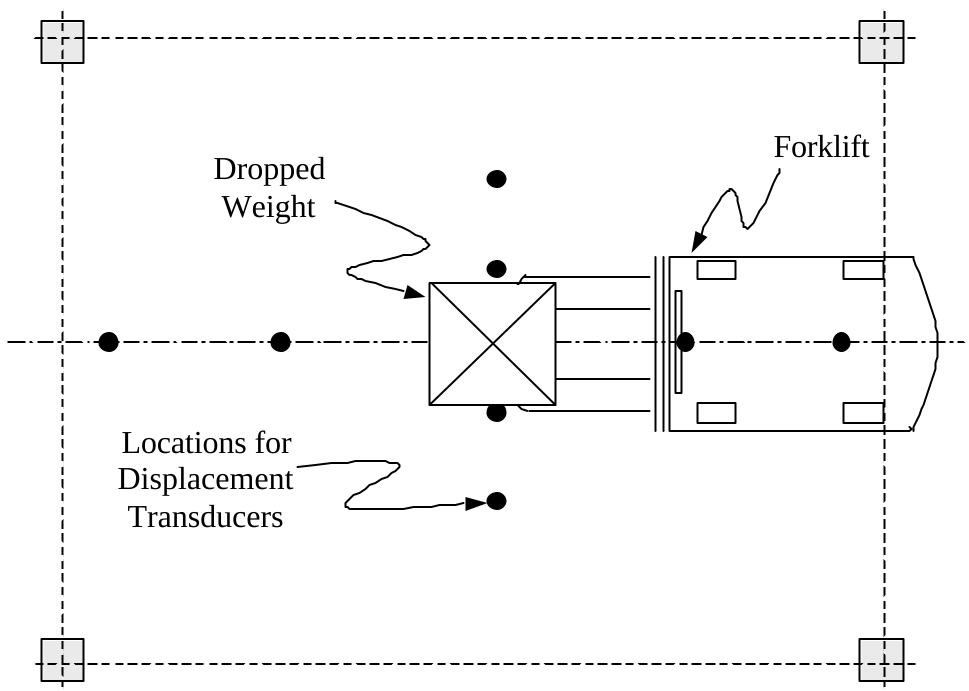

Figure 2.13: Plan view of dropped weight test method

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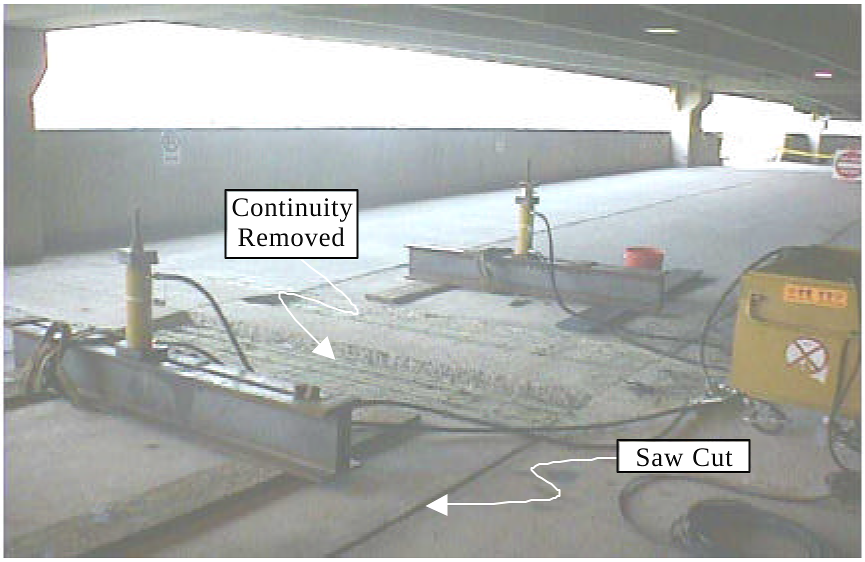

Figure 2.14: Removing continuity allows for true simply supported condition

Figure 2.15: Hydraulic jacks used to apply load

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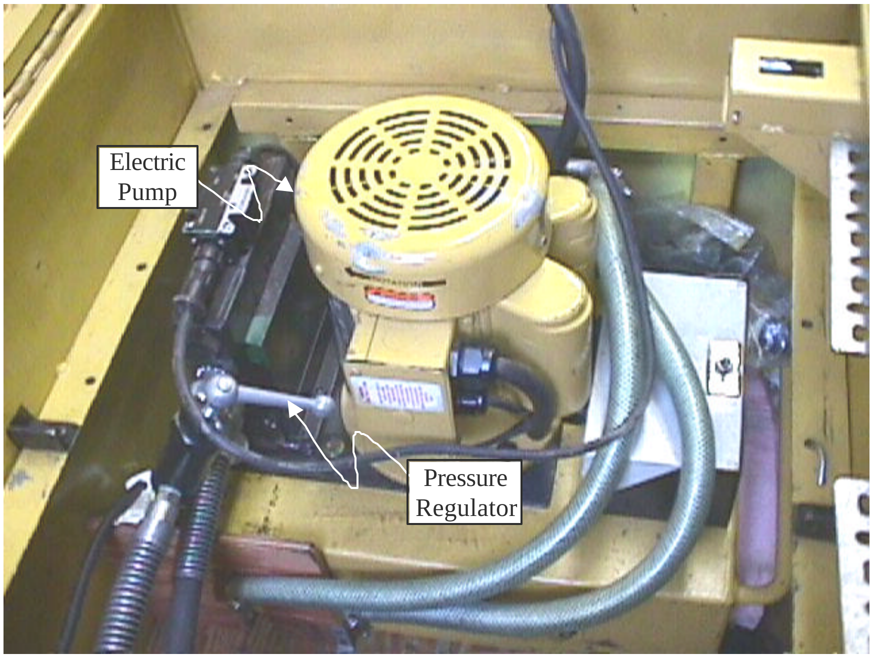

Figure 2.16: Electrical pump used to supply fluid to hydraulic jacks

Figure 2.17: Manual pump used to supply fluid to hydraulic jacks

Figure 2.18: Electrical pump transport box

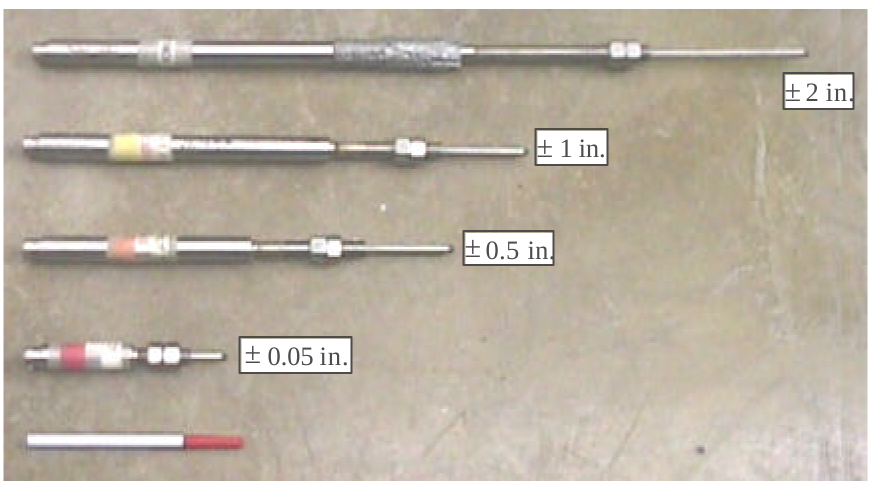

Figure 2.19: LVDTs used to measure deflection

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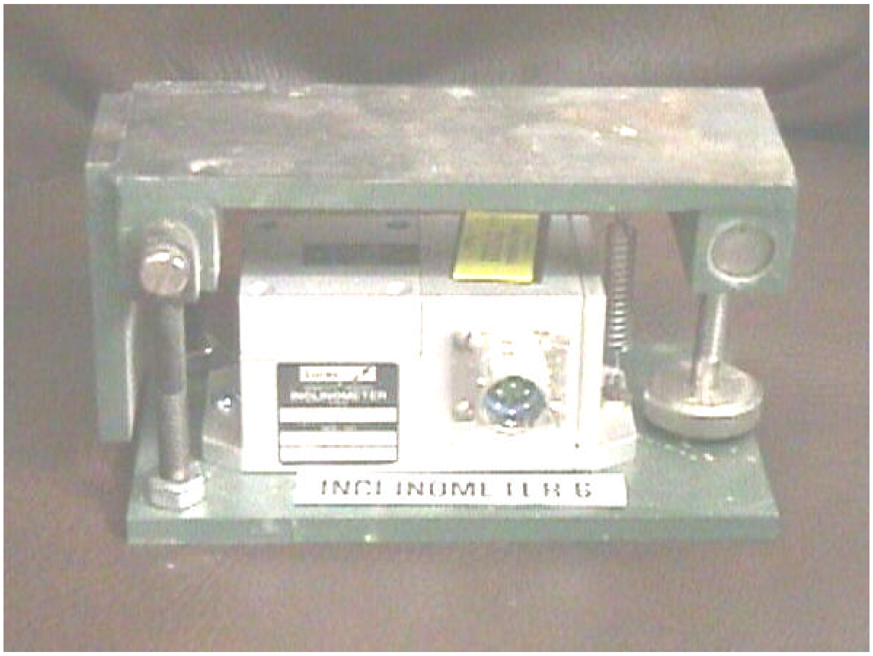

Figure 2.20: Inclinometers used to measure slope

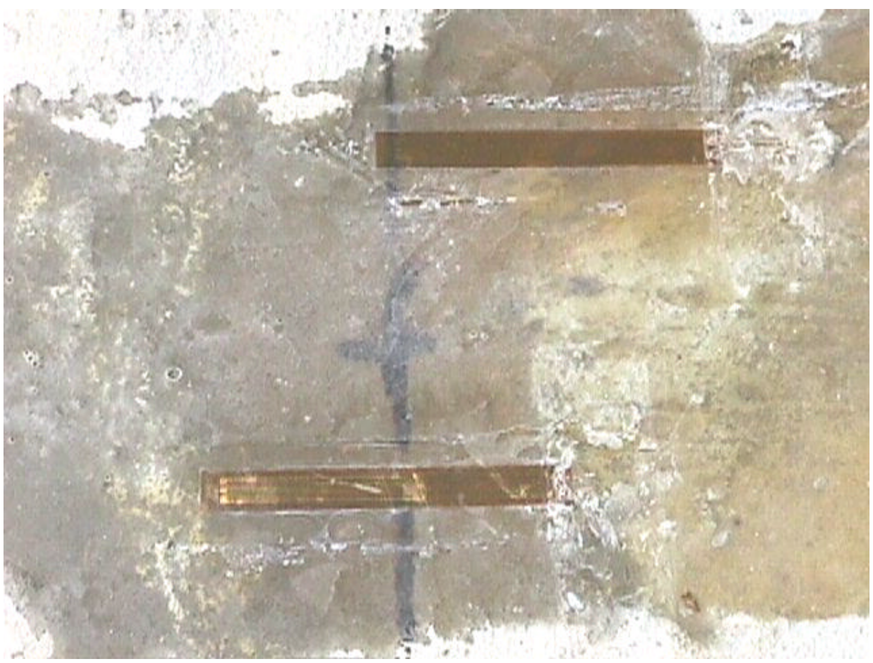

Figure 2.21: Strain gages used to measure the compression strain in concrete

Figure 2.22: Extensometers used to measure the strain across a crack and crack widths

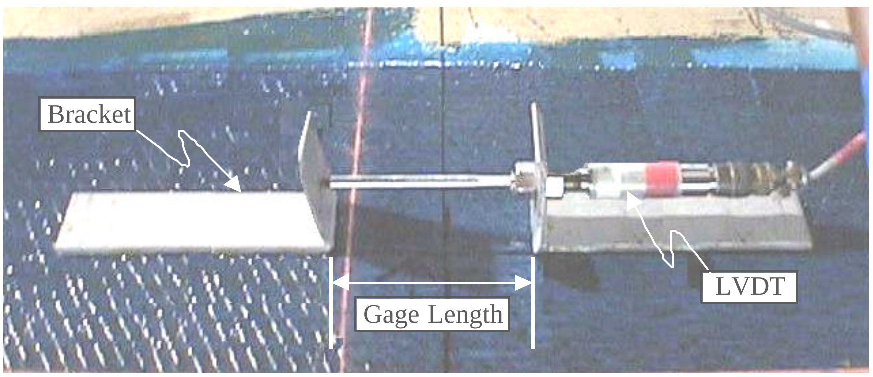

Figure 2.23: LVDT used to measure the average strain over a gage length

Figure 2.24: Load cells used to measure applied load

Figure 2.25: Data acquisition system collects data continuously from several devices

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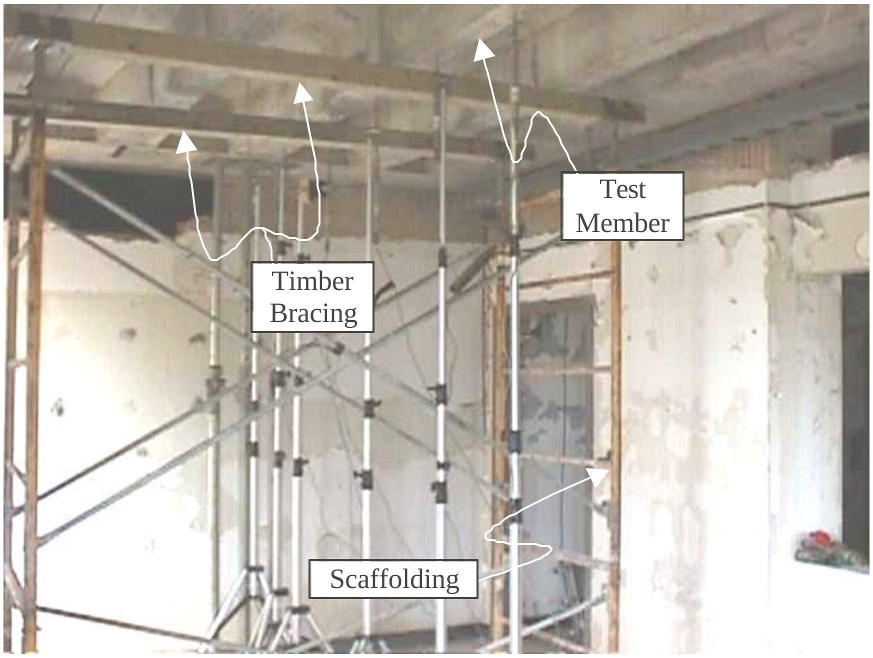

Figure 2.26: Scaffolding used to prevent total collapse of tested member

CHAPTER 3 PERFORMING A RAPID LOAD TEST

The protocol defined in the following sections is a generic guideline. The engineer may wish to modify this protocol to meet the needs of a specific project.

3.1 Procedure for Rapid Load Testing

The rapid load test involves applying load in quasi-static load cycles. The full test of a member is comprised of six load cycles with the modality shown in Figure 3.1. (In this figure, the vertical axis reports the applied test load as a percentage of the maximum value to be applied. The horizontal axis reports the cumulative time, in minutes, as the test proceeds.) Each individual load cycle (defined on Figure 3.1 by a circled letter) includes four to six load steps. Any given load cycle consists of an initial, minimum load level; a step-wise increase in load up to a relative maximum load level; and a return back to the initial value. As shown on the figure, each load cycle is repeated at least one time using of the same load steps and load levels. The level of load achieved through each step and each cycle may be subject to change depending on the behavior of the structure under any given load. The number of cycles and the number of steps listed below should be considered as a minimum.

- <u>Benchmark:</u> At the beginning of the rapid load test an initial reading of the instrumentation should be taken at least 1 minute after all the equipment is functioning and no load is being applied to the test member, other than the testing equipment. The benchmark is shown in Figure 3.1 as the constant line beginning at time zero and indicating no load. After initial values have been recorded, the load test commences with the first cycle.

- <u>Cycle A:</u> The first load cycle consists of load steps, each increased by no more than 10% of the maximum total load expected in the rapid load test. The load is increased in steps, until the service level of the member is reached, but no more than 50% of the maximum anticipated test load, as shown in Figure 3.1. At the end of each load step, the load should be maintained until the parameters, which define the response of the structure (e.g., deflections, rotations, strains, etc), have stabilized, but not less than 1 minute. The maximum load level for the cycle should also be maintained until the structural response parameters have stabilized, but no less than 2 minutes. Holding the test load until the structural response has stabilized shows that the member has "realized the effects of that load to an acceptable degree" (FitzSimons and Longinow, 1975). For response parameters to be considered stable, the recorded values in the second half of the time interval under a constant load should not exceed 15% of those attained in the first half of the time interval. If this condition is not met after the minimum time interval, the load should be maintained until such time that it is met or the member has been deemed unsafe. Changes in the applied load should be made "quasi-statically." Essentially, changes in load must be slow enough so that structural response parameters can be monitored. While unloading, the load should be held constant at the same load levels as the loading steps for at least 1 minute, as shown in the figure. In certain instances, it may be impractical to completely unload the member at the end of each cycle. In those cases, the load may be held at no more than 10% of the maximum anticipated test load, which is shown by the shaded region in Figure 3.1.

- <u>Cycle B:</u> The second load cycle, Cycle B, is a replica of the first cycle, Cycle A, as shown in Figure 3.1. By duplicating a load cycle, one is able to check the repeatability of the structural response parameters at each load step. If a significant difference appears between two consecutive and equal cycles, the load test should be halted and the structure should be reevaluated. The load cycles are also repeated, because the first load cycle is often used for the “bedding-in” of the system (Bungey, 1989).

- Cycles C and D: Load Cycles C and D are identical and achieve a maximum load level that is approximately half way between the maximum load level achieved in Cycles A and B and 100% of the total anticipated test load. The load steps at the beginning of Cycles C and D may be greater than 10%, but only up to the load level that was attained in Cycles A and B. It is often helpful to repeat some of the load steps taken in the Cycles A and B to again check the repeatability of the test member, as shown in Figure 3.1. As the level of load exceeds that attained in the Cycles A and B, the load steps should again not be greater than 10% of the maximum expected test load. Each load level in Cycles C and D is maintained until the structural response parameters have become stable, but not less than 1 minute, and 2 minutes for the relative maximum.
- Cycles E and F: Similarly, the fifth and sixth load cycles, E and F respectively, should be identical, and they should reach the maximum anticipated test load, as shown in Figure 3.1. The load steps up to the load level attained in Cycles C and D may be larger than 10%, but repeating some of the load levels allows for the repeatability check. Once the level of load becomes greater than that achieved in the Cycles C and D, the load steps should not be larger than 10% of the maximum anticipated test load. Each load step should be repeated as the load is being decreased in each cycle.
- Additional Cycles: In some instances, additional load cycles may be required in order to show the members ability to hold the maximum test load. Additional cycles should be identical to Cycles E and F as defined above.
- Final Cycle: At the conclusion of the final cycle, the test load should be decreased to zero, as shown for Cycle F in Figure 3.1. A final reading should be taken no sooner than two minutes after the entire test load, not including the equipment used to apply the load, has been removed.

3.2 Analysis during testing

Monitoring the structural response during testing to ensure stability of the system at every load level is key to the performance of a successful rapid load test. The stabilization of the structural response parameters under a constant load shows the member's ability to safely maintain that load. Monitoring additional parameters (i.e., repeatability, deviation from linearity, and permanency) during a rapid load test also gives an indication of the behavior of the test member.

- Repeatability: One method of rating a structure’s performance during a rapid load test is by checking the repeatability of some structural responses, typically deflection. Repeatability, calculated using Equation 3.1 with reference to Figure 3.2, is a ratio of the difference between the maximum and residual deflections recorded during the second of two identical load cycles to that of the first. During a rapid load test, if the load is not decreased to zero at the end of each cycle, the origin of the load versus deflection curve is shifted to P_{min}, as shown in Figure 3.2, in order to calculate repeatability.

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$$Repeatability = \frac{D^B_{max} - D^B_r}{D^A_{max} - D^A_r} \times 100\% \qquad \textbf{Equation 3.1}$$

The quantities in Equation 3.1 and shown in Figure 3.2 are defined as follows:

P_{max} = maximum load level achieved by Cycles A and B

P_{min} = minimum load level achieved at the end of Cycles A and B

D^B_{max} = maximum deflection in Cycle B under a load of P_{max}

D^B_r = residual deflection after Cycle B under a load of P_{min}

D^A_{max} = maximum deflection in Cycle A under a load of P_{max}

D^A_r = residual deflection after Cycle A under a load of P_{min}

If a test member incurs a greater net deflection under a particular load the second time as opposed to the first, this may be an indication that the member has been softened. Experience has shown that a repeatability of greater than 95% is satisfactory. By checking the repeatability of deflections, one is not only monitoring the structure's behavior, but also gaining assurance that the data collected during the rapid load test is consistent.

- Deviation from Linearity: Deviation from linearity is a measure of the nonlinear behavior of a member being tested. As a member becomes increasingly more damaged, its behavior may become more nonlinear, and its deviation from linearity may increase. The rapid load test method of applying load in cycles provides the opportunity to calculate the deviation from linearity in a variety of ways. The following illustrates how deviation from linearity is calculated for the load-deflection envelope of the test member.

  In order to calculate the deviation from linearity, linearity must be defined. Linearity is the ratio of the slopes of two secant lines intersecting the load-deflection envelope. The load-deflection envelope is the curve constructed by connecting the points corresponding to only those loads, which are greater than or equal to any previously applied loads, as shown in Figure 3.3. This figure is a plot of load, on the vertical axis, versus deflection, on the horizontal axis, for a member undergoing a load test consisting of six cycles, labeled A through F. Given a point *i* with coordinates P_i and D_i, the secant line, shown as a dashed line in Figure 3.3, is drawn from the origin to the point *i* on the load-deflection envelope, and α_i is its slope. The reference secant line is the one that joins the origin to a reference point having coordinates P_{ref} and D_{ref}, where P_{ref} is 50% of the maximum anticipated test load for the rapid load test, P_{max}. The linearity of any point *i* on the load-deflection envelope is the percent ratio of the slope of that point's secant line, α_i, to the slope of the reference secant line, α_{ref}, as shown in Equation 3.2.

$$Linearity_i = \frac{\alpha_i}{\alpha_{ref}} \times 100\% \qquad \textbf{Equation 3.2}$$

  The deviation from linearity of any point on the load-deflection envelope is the compliment of the linearity of that point, as shown in Equation 3.3.

$$Deviation\ from\ Linearity_i = 100\% - Linearity_i \qquad \textbf{Equation 3.3}$$

Once the level of load corresponding to the reference load has been achieved, deviation from linearity should be monitored until the conclusion of the rapid load test. Experience (Mettemeyer, 1999) has shown that the values of deviation from linearity, as defined above, are less than 25%. Research is being conducted in this area in order to determine if deviation from linearity can be used to predict failure. Deviation from linearity may not be useful when testing a member that is expected to behave in a nonlinear, but elastic manner. For such members, repeatability, as defined above, and permanency, as defined below, may be better indicators of damage in a tested structure.

- Permanency: The amount of permanent change displayed by any structural response parameter during any given load cycle is defined as permanency. Deflection permanency, calculated using Equation 3.4, may only be legitimately calculated for the second cycle of two identical load cycles, for example, Cycle B in Figure 3.2. Often a system will seem to have suffered a much larger permanent deformation in the first of two identical load cycles because of the "bedding-in" of the system. In Equation 3.4, Δ_r is the residual deflection and Δ_{max} is the maximum deflection that has occurred in the member during a single cycle.

$$Permanency = \frac{D_r}{D_{max}} \times 100\% \qquad \textbf{Equation 3.4}$$

Experience has shown that a deflection permanency of less than 10% is acceptable. Bares and FitzSimons (1975) suggested that 25% permanency is acceptable for RC structures and 20% permanency for PC structures.

3.3 Interpreting the Results

In some instances, it may be sufficient to show the member's ability to hold a given load as a proof of successful performance. However, often it is helpful to perform a more in-depth analysis of the data.

3.3.1 Analytical Modeling

Once the rapid load test has been conducted, analytical models can be used to verify assumptions regarding load sharing characteristics of adjoining members, effects of a concentrated load versus a distributed load, and degree of support fixity. The analytical model can be refined by adjusting the boundary conditions and stiffness of the adjacent elements to match the actual measured deformed shape of the structure. Once these refinements have been made, the analytical model may also be used to accurately determine the internal forces caused by the test loads.

For example, when testing in flexure a two-way slab with symmetric boundary conditions, a concentrated load is applied at mid-span of the test element that will produce the same moment per unit width at the critical section (i.e., mid-span) as that caused by a uniformly distributed load. Equation 3.5 is used to determine the magnitude of the uniformly distributed load that is simulated by the concentrated test load.

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$$w_{sim} = \frac{P_T}{C_1 \times C_2 \times l_1 \times l_2}$$ **Equation 3.5**

The variables shown in Equation 3.5 are defined as follows:

w_{sim} = uniformly distributed load simulated by the test load

P_T = magnitude of a concentrated test load

C_1 = multiplier to account for contribution of adjacent elements

C_2 = multiplier to account for distributed load versus point load

l_1 = span in the primary direction

l_2 = span in the perpendicular direction

The coefficient C_1 accounts for the contribution of the adjacent elements (load sharing) to the member's response to loading. The value of C_1 is essentially the width of the slab that is effective in resisting the applied load on the test member. Based on deflection values collected in either a preliminary test or under low levels of load, the value of C_1 can be more accurately defined. Following the same example discussed earlier, the value of C_1 for a unit strip of a two-way slab with symmetric boundary conditions tested in positive flexure can be calculated using Equation 3.6.

$$C_1 = \frac{l_2 \times \sum_{i=1}^{n} D_i}{2 \times D_1 \times b \times n}$$ **Equation 3.6**

The values shown in Equation 3.6 are defined as follows:

D_i = deflection measured at point i

D_1 = deflection measured under the load

b = width of the unit strip

n = number of equally spaced deflection readings orthogonal to the span of the test member

The coefficient C_2 accounts for the difference between applying a concentrated load and a uniformly distributed load to the test member. For example, consider the case of a load test on a simply supported beam where the concentrated load is applied at mid-span in order to produce a maximum positive moment equal to that of the same beam subjected to a uniformly distributed load. In this case, C_2 is equal to 0.5. Values for C_2 can be computed for every level of fixity from 0%, simply supported, to 100%, fixed. The level of fixity for a given member can be determined by computing R, the ratio of the net deflection at quarter-span to that at mid-span. The highest value of R corresponds to a span with pinned ends (no rotational stiffness) and the lowest value indicates a fully fixed support condition. The values of R and C_2 can be plotted on separate vertical axes versus the percent fixity of the supports. Figure 3.4 shows a sample curve for the case of a span with symmetric boundary conditions loaded with a concentrated load that produces a moment at mid-span equivalent to that due to a uniformly distributed load. Similar curves can be generated for other arrangements in loading, simulated response conditions, and/or boundary conditions.

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Upon completion of a preliminary test, or lower load cycles, the value of *R* can be computed as the average of all the values calculated based on measurements taken at load levels within the elastic range. Knowing *R*, fixity and C_2 can be found as shown by the example in Figure 3.4.

By applying the proper level of support fixity to the analytical model, the shape of the analytical and experimental elastic curves will be similar. The match between measured and analytical deflection values can be obtained by adjusting the concrete elastic modulus assumed in the model.

Once a satisfactory agreement between measured and analytical deflections is confirmed, the model is then used to accurately determine the magnitudes and variations of bending moments in the slab.

3.3.2 Analysis of Data

Experience has shown that graphical as well as numerical efforts may aid in the understanding of the structure's response to a rapid load test. The most common graphical aides include curves displaying load and a structural response parameter plotted versus time and load plotted versus a structural response parameter. Numerical efforts include the calculation of permanency as a criterion for the acceptable performance of the test member.

- <u>Load and Structural Response Parameters versus Time:</u> A "Time History" of a rapid load test is a graph of load and some structural response parameter plotted on dual vertical axes versus time. This graph shows the stabilization of that specific structural response parameter under a constant load. It can also be used to show the repeatability of the structural response of two identical load cycles.
- <u>Load versus Structural Response Parameters:</u> A complete plot of the load versus any structural response parameter is a way to show the linear and elastic behavior of the test member. Members approaching failure may show signs of nonlinear or inelastic behavior. Residual deformations are also clearly shown. It is helpful to plot the theoretical response along with the actual results.
- <u>Permanency:</u> Permanency, as described above and shown in Equation 3.4, may be used as a criterion that defines the acceptable performance of a test member under a given load. Permanency as an acceptance criterion should only be that which is calculated for the final cycle of the rapid load test. Additional repetitions of the final cycle may be required. If the permanency value used as a criterion for acceptance is near the pre-established limit, one may wish to include the calculations of repeatability and deviation from linearity in the post-testing analysis.

Appendix A, in this document, contains analysis and discussion of five rapid load tests. One member was tested in a controlled laboratory environment, and four others were tested in an existing structure. Some of the calculations performed on the data collected during the rapid load tests are summarized in Table 3.1. Appendix A also compares the results of these rapid load tests with those achieved by 24-hour load tests run on the same specimens. After the rapid and 24-hour load tests, each member was taken to failure in order to determine its true capacity. Appendix B, in this document, discusses some commercial applications of this rapid load testing technology.

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Table 3.1: Summary of calculations for five case studies in Appendix A

Case Study	Member Type	Permanency of Final Cycle (%)	Maximum Deviation from Linearity (%)	Minimum Repeatability (%)
#1	PC Double Tee	4	12	98
#2	RC Joist (JS3B)	5	21	>100
#3	RC Joist (JS5B)	0	19	>100
#4	RC Joist (JL3B)	3	20	>100
#5	RC Joist (JL4B)	2	20	>100

3.3.3 Conclusions based on results

Once the numerical and graphical analysis has been completed, conclusions as to the acceptable performance of the member under the loads applied can be drawn. This method of testing only quantifies a safe level of load for a member under short-term conditions. Long-term behavior influenced by phenomena, such as creep and degradation, must be characterized separately from this testing procedure.

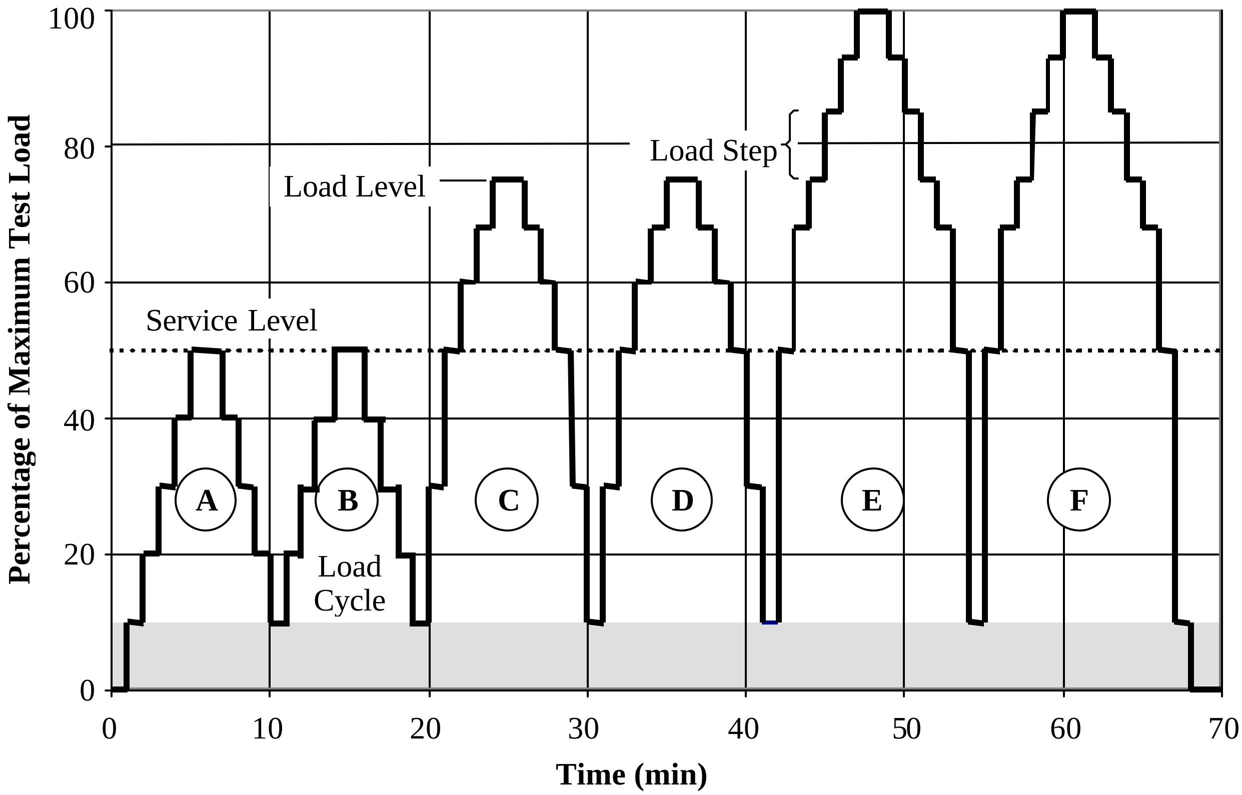

Figure 3.1: Load steps and cycles for a rapid load test

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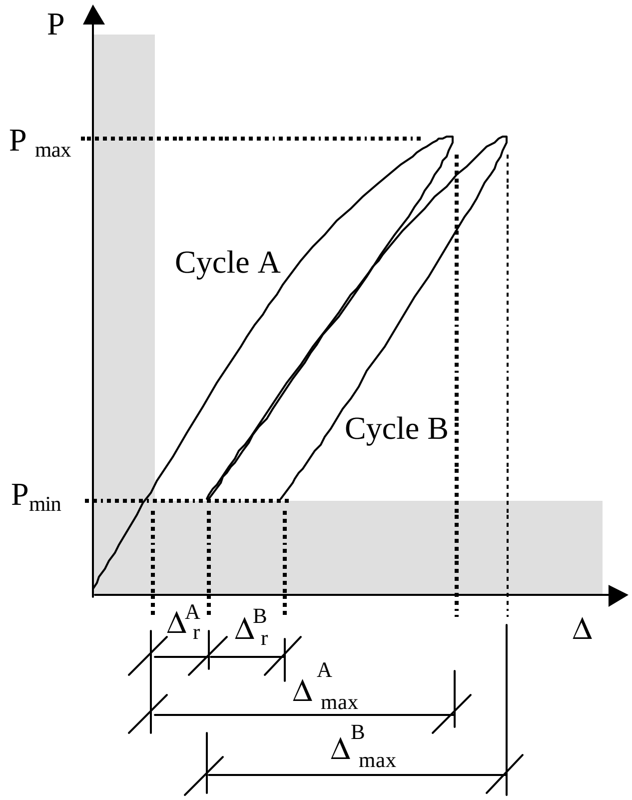

Figure 3.2: Sample load versus deflection curve for two cycles

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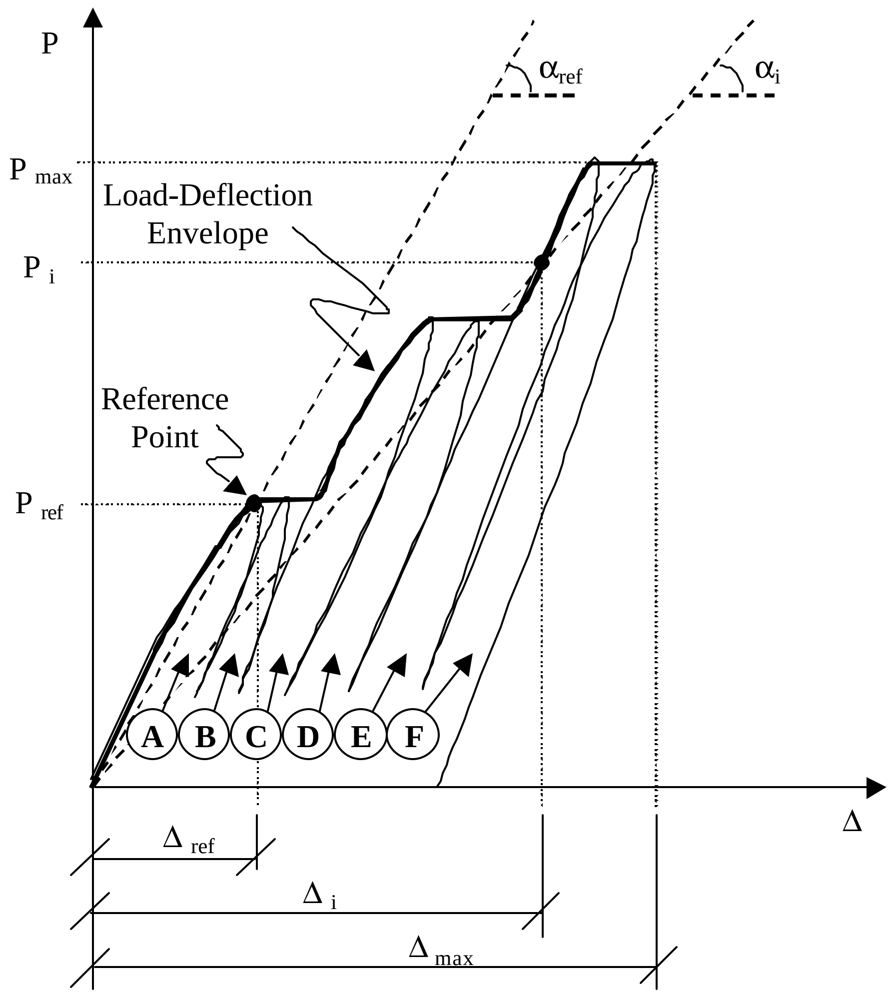

Figure 3.3: Sample load versus deflection curve for six cycles

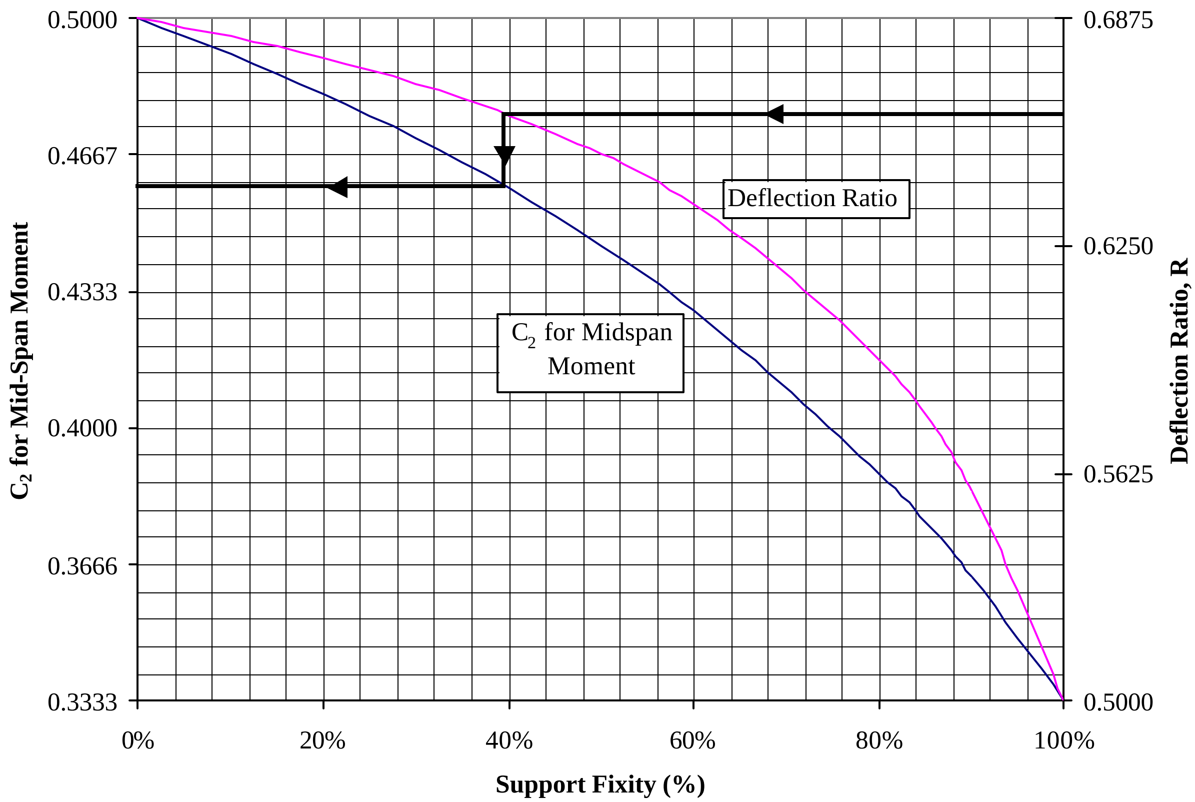

Figure 3.4: Variation of C_2 and R for a symmetrically bound member loaded at mid-span

CHAPTER 4 CONCLUSIONS

Load testing has long been a valuable tool in the evaluation of a structure whose capacity is in question due to design/construction flaws, the use of strengthening systems, deterioration, unique design, or change in use. Historically, load tests have been conducted using weights (e.g. water, sand) for the application of load and structural responses have been monitored by hand (e.g. dial gages), both of which are very time-consuming. Recent advances in technology in the areas of load application and response monitoring have automated the process of load testing; however, guidelines have not taken advantage of them. This document provides guidance to the engineer on how load tests can be performed in an efficient and cost-effective manner. The rapid load test protocol consists of three main phases: planning for the test, performing the test, and evaluating the results.

A well-designed rapid load test includes a preliminary investigation involving a study of the geometry, loading history, and material characteristics of a structure. Using the gathered information, structural analysis is used to determine the magnitude of the concentrated test load that will result in the desired effect. Certain concepts, unique to this load testing technique, are discussed (e.g. effects of a concentrated versus a distributed load). Methods of load application and equipment that have been successfully used are also discussed. All steps involved in the planning of a rapid load test are clearly stated in a plan of action and need to be submitted to the client or his/her representative for approval before the execution of the load test.

A rapid load test consists of concentrated loads being applied in a quasi-static manner in at least six load cycles, with each cycle containing several load steps. The initial cycles achieve relatively low levels of load and are used to verify assumptions made in the preliminary analysis and ensure stability of the system. Each load step is maintained until the member has displayed sufficient capacity, 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.

Once the load test has been completed, the performance of the member can be evaluated based on both graphical and numerical analysis. Acceptance criteria that provide a means of rating the performance of a member during a rapid load test are defined. A rapid load test offers easy-to-understand results, which give the client confidence in the capabilities of a structural member. Using information gained from the load test concerning the effects of concentrated versus distributed loads, support conditions, load sharing of adjacent members, and composite action of structural and nonstructural elements, accurate analytical models can be used to determine the internal forces induced by the test loads.

A flow chart documenting the major steps involved in planning, performing, and evaluating a rapid load test are summarized in the figure that follows:

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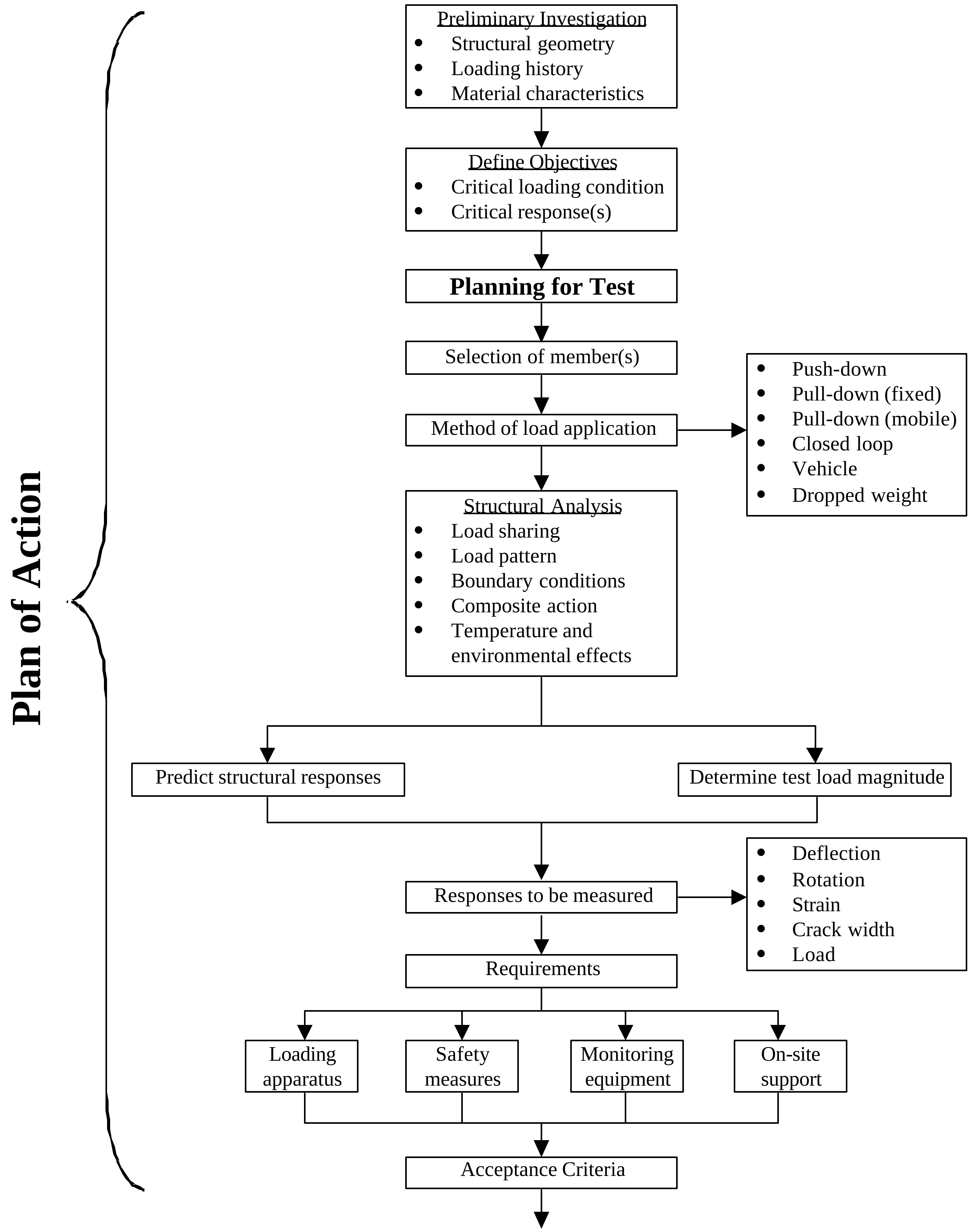

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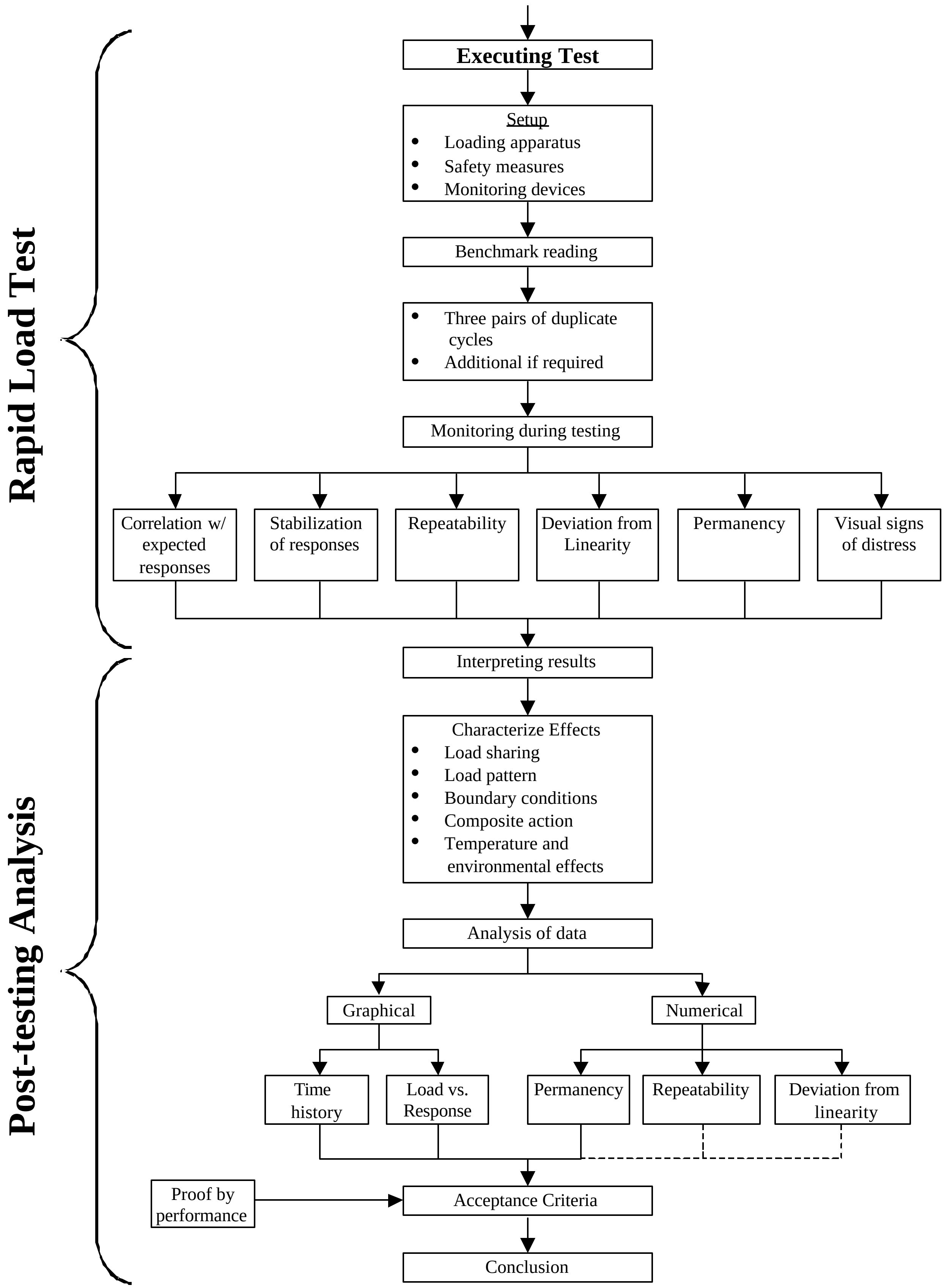

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APPENDIX A VALIDATION OF RAPID LOAD TESTING PROCEDURE

Five case studies are described in order to demonstrate the applicability of the rapid load testing procedure defined in this document. A varying number of cycles and load steps per cycle were used in the rapid load tests. Each structural member was also held under sustained load for 24 hours for comparison. The results from the rapid load tests and the 24-hour load tests are discussed in the sections that follow. After the rapid and 24-hour load tests, each member was taken to failure in order to determine its true capacity. Additional information regarding the case studies discussed in this appendix can be found in Huang (1999), Mettemeyer (1999), and Raghu (2000).

Case Study #1: Prestressed Double Tee Beam

The initial efforts in the development of an in situ rapid load testing protocol took place in a controlled laboratory environment. A full-size, PC double tee section with dap ends was the first member tested comparatively for a short duration and for 24 hours. The shear capacity of the dap end of the member, typical of those used in parking facilities, was in question. Initially, a rapid load test was run on the member, and structural response measurements (i.e., deflection, strain, and rotation) were recorded at 1-second intervals. Upon completion of the rapid load test, the member was then loaded for 24 hours to the same maximum load as achieved during the rapid load test. Measurements of the member's responses were recorded at 10-second intervals throughout the duration of the 24-hour test. Upon completion of the 24-hour load test, the member was failed in order to determine its true capacity.

Figure A.1 and Figure A.2 show the test setup used for the rapid load test, the 24-hour load test, and the test to failure. The hydraulic jacks, when extended, applied an upward force under the dap end of each stem of the double tee. The steel structural shape, that was held in place by the high-strength steel bars anchored to the floor, sat on plywood on top of the double tee beam and provided a reaction against the upward movement caused by the hydraulic jacks, as shown in Figure A.1. The plywood protected the concrete from any localized damage and concentrated the load on the two stems of the double tee. The far end of the double tee beam was simply supported. The concept was to cause a shear force in the dap end equivalent to that which would be produced by a uniformly distributed load greater than 85% of the factored design loads. The location of the steel structural shape was such that failure of the dap end would be controlling. Because the jacks had to produce enough force to lift the beam before engaging the reaction; one fourth of the self-weight of the specimen was subtracted from the readings of applied load to each stem. Consistently with this, the net upward deflection of the member is the result of the measured deflection minus its rigid body movement.

Figure A.3 is a time history of the load and net deflection for the rapid load test, and Figure A.4 is the same for the 24-hour load test. In both figures, the horizontal axis displays the cumulative time, in hours and minutes, as both the rapid and the 24-hour load tests progressed. The left vertical axis, on both Figure A.3 and Figure A.4, shows the amount of load applied to each stem of the double tee as described above. The right vertical axis on each figure shows the net deflection at the end of the specimen as described above. Also shown on the figures is a schematic drawing of the test configuration. The symbols, labeled with "#6" and "#11", represent LVDTs measuring the deflections at the location of the steel beam and at the end of the specimen, respectively. The data collected from these two devices were used to plot the net deflection at the end of the specimen. The thin line plotted in Figure A.3 and Figure A.4 represents the applied load, and the thick line represents the net deflection, both with respect to time. Shown on Figure A.3 is the stabilization of deflections under a constant load within the first minutes of load application in the first two cycles. The deflection in the third and fourth cycles did not stabilize, as defined in Section 3.1. In addition, the fourth cycle, a repeat of the third cycle, shows that deflections were larger. The repeatability, calculated as described in Section 3.2, is 98%. However, because the load was not maintained in the fourth cycle until the deflections had stabilized, the deflection achieved in the 24-hour test under the same maximum load, as shown in Figure A.4, was slightly larger than that from the rapid load test. This occurrence illustrates the importance of waiting until deflections are stable. Also shown in Figure A.4 is a very small increase in the deflection during the period of constant loading. This insignificant increase in deflection could be attributed to the opening of some flexural cracks.

Figure A.5 shows the load versus net deflection curve for the beam as it was taken to failure. Again, the load shown on the vertical axis is that which was applied to each stem of the double tee minus one fourth of the self-weight of the specimen. The horizontal axis shows the net deflection of the member at the end, as described above. In Figure A.5, the light gray line shows the behavior of the specimen as it was repeatedly loaded and unloaded. The darker line represents the load-deflection envelope as defined in Section 3.2. This load deflection envelope was used to calculate the deviation from linearity for the rapid load test. The maximum deviation from linearity experienced during the rapid load test was 12%. The maximum deviation from linearity achieved during the 24-hour test was 22%.

Permanency for the third and fourth cycles of the rapid load test, as well as that for the 24-hour test, were calculated. In order to overcome the effects that the dead weight of the specimen would have in reducing the permanency under no applied load, these values were calculated using a minimum load level of 2300 lbs. (10.2 kN). The permanency, as described in Section 3.2, calculated for the third and fourth cycles of the rapid load test was 6% and 4%, respectively. The permanency of the 24-hour test was 3%. These low levels of permanency, as well as the decreases in the permanency, as load cycles to the same load level were repeated, help show that the member has acceptable performance.

In Figure A.5, the deflection behavior near the failure load had to be projected because the LVDTs were removed from the specimen in order to prevent damage to them upon failure of the member. The dashed line up to the failure load is this projection. Figure A.6 shows that the beam failed due to a shear crack at the reentrant corner of the dap end, as expected. The dark colored material on the surface of the specimen is the external FRP reinforcement that was being investigated.

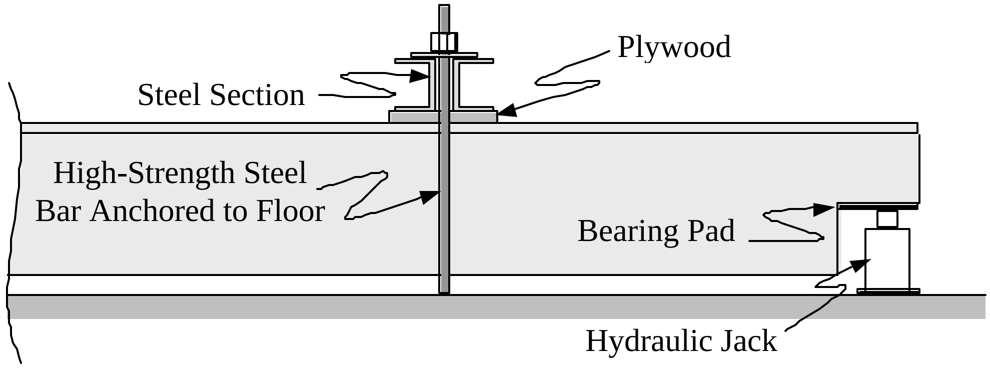

Figure A.1: Side view of setup for testing of PC double tee

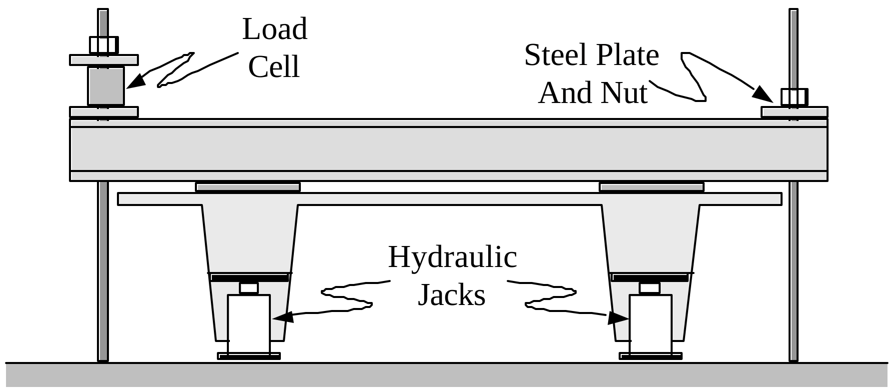

Figure A.2: End view of setup for testing of PC double tee

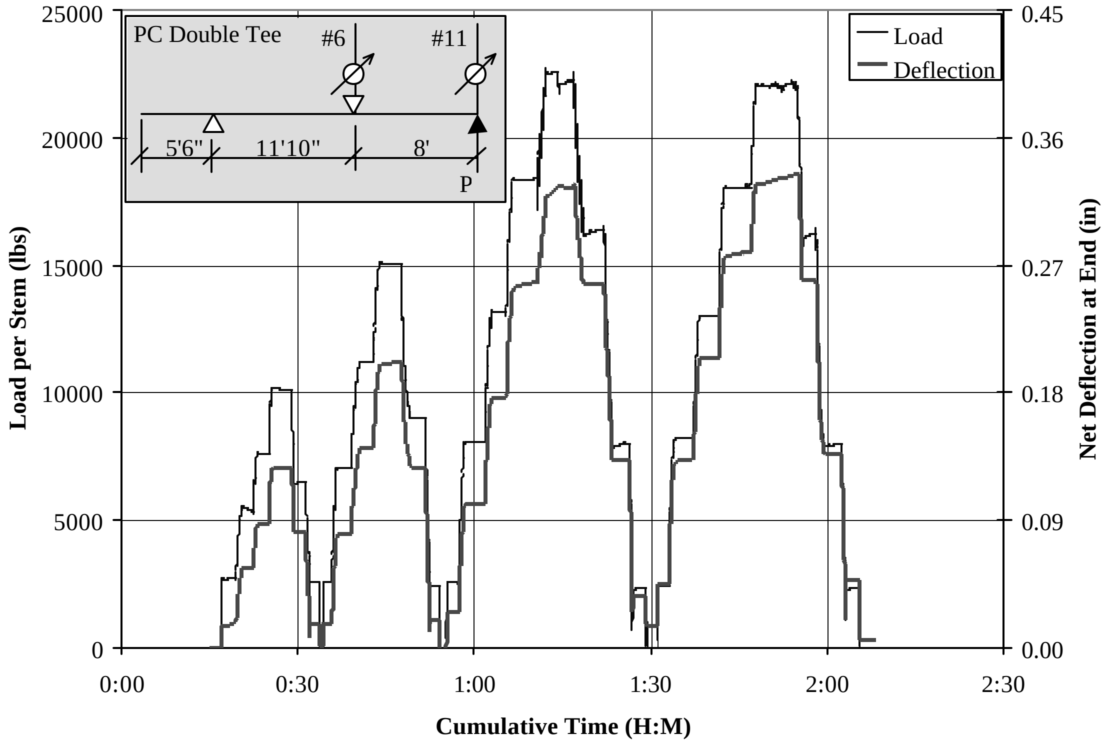

Figure A.3: Time history of rapid load test for PC double tee
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

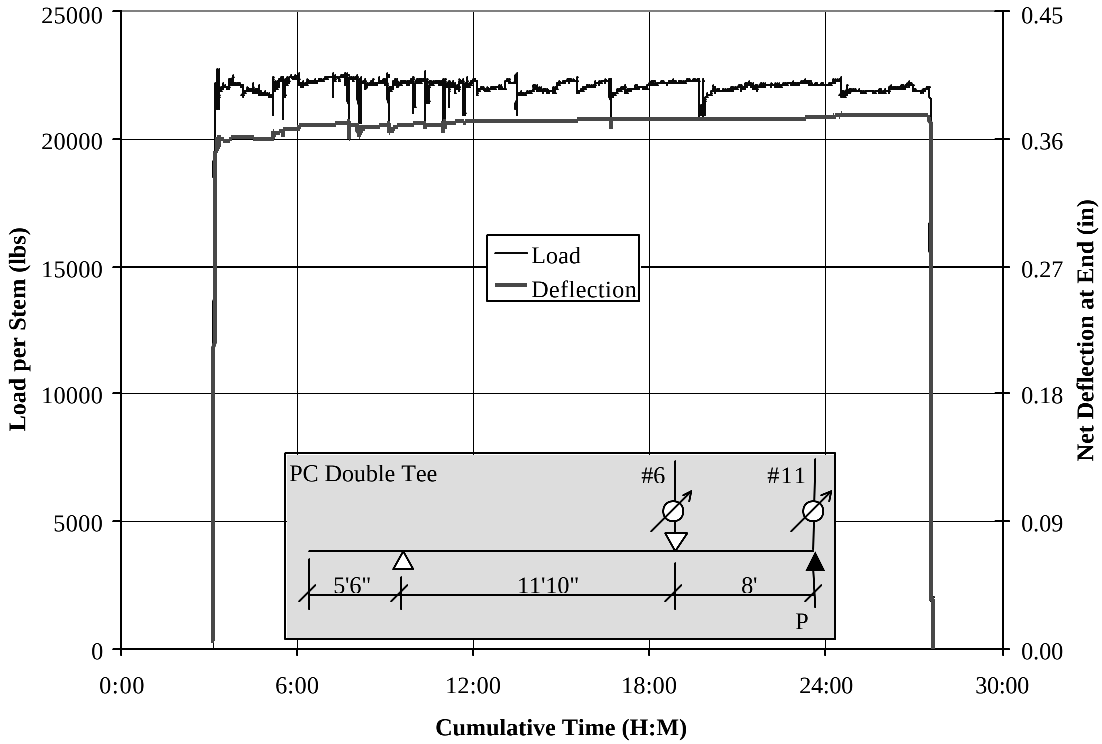

Figure A.4: Time history of 24-hour test of PC double tee
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

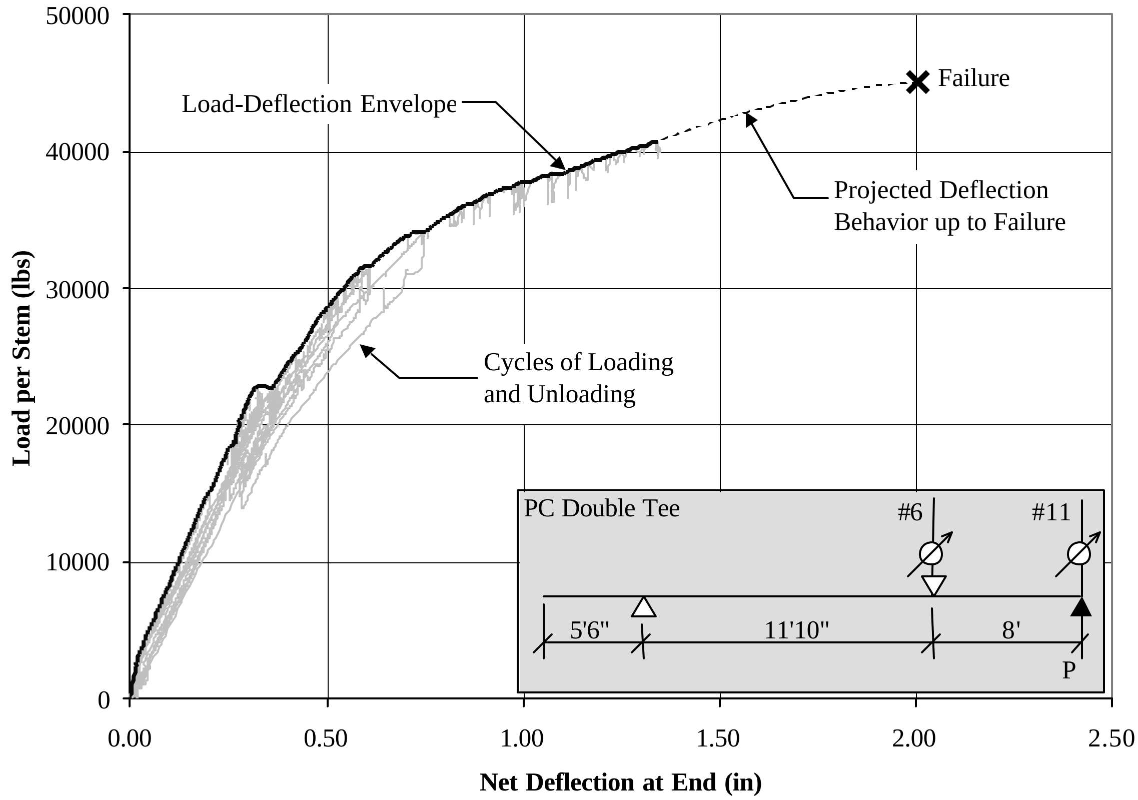

Figure A.5: Load versus deflection curve for PC double tee
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

Figure A.6: Shear failure in the dap end of the externally strengthened PC double tee

Case Study #2: Short Span Ceiling Joist (JS3B)

The use of a decommissioned RC structure offered a unique research opportunity (Mettemeyer, 1999 and Raghu, 1999). Twenty RC joists were tested using the rapid load testing technique and each member was also taken to failure to determine its true capacity. All 20 joists were cut into tee sections by isolating them from the rest of the slab. Sixteen members were strengthened using externally bonded FRP sheets in order to validate their behavior in situ. The remaining four joists were tested as control specimens. Case Studies #2 through #5 discuss four of the strengthened members that were also tested comparatively for 24 hours. The locations of these four joists are lightly shaded in Figure A.7. This figure is the floor plan of both the third and fourth floors of the structure. Case Study #2, JS3B, was located near the central portion of the plan, on the third floor. Case Study #3, JS5B, was located on the fourth floor, directly above JS3B. Case Study #4, JL3B, was a long span member on the fourth floor, located in the lower-left hand corner of the plan. Case Study #5, JL4B, was a long span member on the fourth floor, located in the lower-right hand corner of the plan. Initially, a rapid load test was run on each member, and structural response measurements (i.e., deflection, strain, and rotation) were recorded at 1-second intervals. Upon completion of a rapid load test, each joist was then loaded for 24 hours to the same maximum load of the rapid load test. Measurements of the structural responses were recorded at 10-second intervals throughout the duration of the 24-hour load tests. Upon completion of the 24-hour load test, the member was failed in order to determine its true capacity. Each load test was conducted using the push down method as described in Section 2.2.2. The setup for the hydraulic jacks on the test member (Figure A.8), the shoring on the floor above the test member (Figure A.9), and the instrumentation below the test member (Figure A.10) are typical. Because of the high level of load resisted by the joists, two hydraulic jacks were used (Figure A.8). The plywood protected the concrete from any localized damage and ensured a consistent footprint. The cribbing was used to raise the jacks high enough to prevent buckling of the extensions. The maximum test loads applied in the rapid and 24-hour load tests caused a shear force at the critical location in each member that was greater than that computed from a uniformly distributed load equal to 85% of the factored design loads.

Figure A.11 is a time history of the load and net deflection for the rapid load test, and Figure A.12 is the same for the 24-hour load test. In both figures, the horizontal axis displays the cumulative time, in hours and minutes, as both the rapid and the 24-hour load tests progressed. The left vertical axis, in both Figure A.11 and Figure A.12, shows the total load applied by the hydraulic jacks. The right vertical axis in each figure shows the net deflection directly under the load. The net deflection of the members was computed as the measured deflections minus the rigid body movement of the members due to support settlement. Also shown on the figures is a schematic drawing of the test configuration. The symbols, labeled with “#4”, “#7”, and “#12” represent LVDTs measuring the deflections at the near end, far end, and under the load, respectively. The collected data from these devices were used to plot the net deflection under the load. On Figure A.11 and Figure A.12, the thin line represents the total applied load, and the thicker line represents the net deflection, both with respect to time. As shown in Figure A.11, the fourth cycle achieved the average maximum load of the third cycle (i.e., 40,000 lbs. (178 kN)) at the same deflection (i.e., 0.09 in (2.3 mm)). The repeatability, calculated as described in Section 3.2, was greater than 100%. The net deflection achieved in the 24-hour test (Figure A.12) was similar to that under the same load during the rapid load test.

Permanency values calculated for the third and fourth cycles of the rapid load test are 12% and 5%, respectively. These low levels of permanency, as well as the decrease in the permanency with repetition, help show that the member is capable of safely maintaining that applied load.

Figure A.13 shows the load versus net deflection curve for the joist up to failure. The failure load, P_{ult}, was approximately 92,000 lbs. (409 kN). The total load applied by the two hydraulic jacks is shown on the vertical axis. The horizontal axis shows the net deflection of the member at the location of the load, as described above. The net deflection under the load at failure was approximately 0.29 in. (7.4 mm). On Figure A.13, the light gray line shows the behavior of the specimen as it was repeatedly loaded and unloaded. The darker line represents the load-deflection envelope as defined in Section 3.2. This load-deflection envelope was used to calculate the deviation from linearity for the rapid and 24-hour tests, as well as the test to failure. Figure A.14 shows a plot of the normalized load versus deviation from linearity. The maximum load level attained in the rapid and 24-hour load tests is approximately 45% of the true capacity of the member, which correlates to a maximum deviation from linearity of about 21%. Figure A.14 also clearly displays the level of load that was required to achieve a 25% deviation from linearity (i.e., $52\%P_{ult}$).

Figure A.15 shows the graph of the total applied load versus the strain in the external FRP reinforcement. The schematic drawing shows the location of the strain gages labeled #21 through #24. This graph shows that a significant increase in strain did not occur until the load level of approximately 49,000 lbs. (218 kN). The linear elastic behavior below this load suggests that the concrete may not have developed shear cracks. Strain gages number 21, 22, and 24 stop functioning before the failure of the member occurred.

Figure A.16 shows the failure of both joists JS3A and JS3B. These joists were strengthened in identical fashion, isolated by a saw cut, and tested separately. The only difference between the two joists is that a 24-hour load test was run on JS3B. After the failure of JS3A, the externally bonded FRP sheet, the dark colored material in the photograph, was removed from the surface in order to expose the shear crack at the support nearest the applied load. The externally bonded FRP sheet was held in place by an end anchor (Khalifa, et al., 1999). The anchor was grooved into the flange of the tee section and fixed in place with epoxy paste. The failure of the members was a result of the extension of the shear cracks through the flange and the fracturing of the concrete surrounding the anchors.

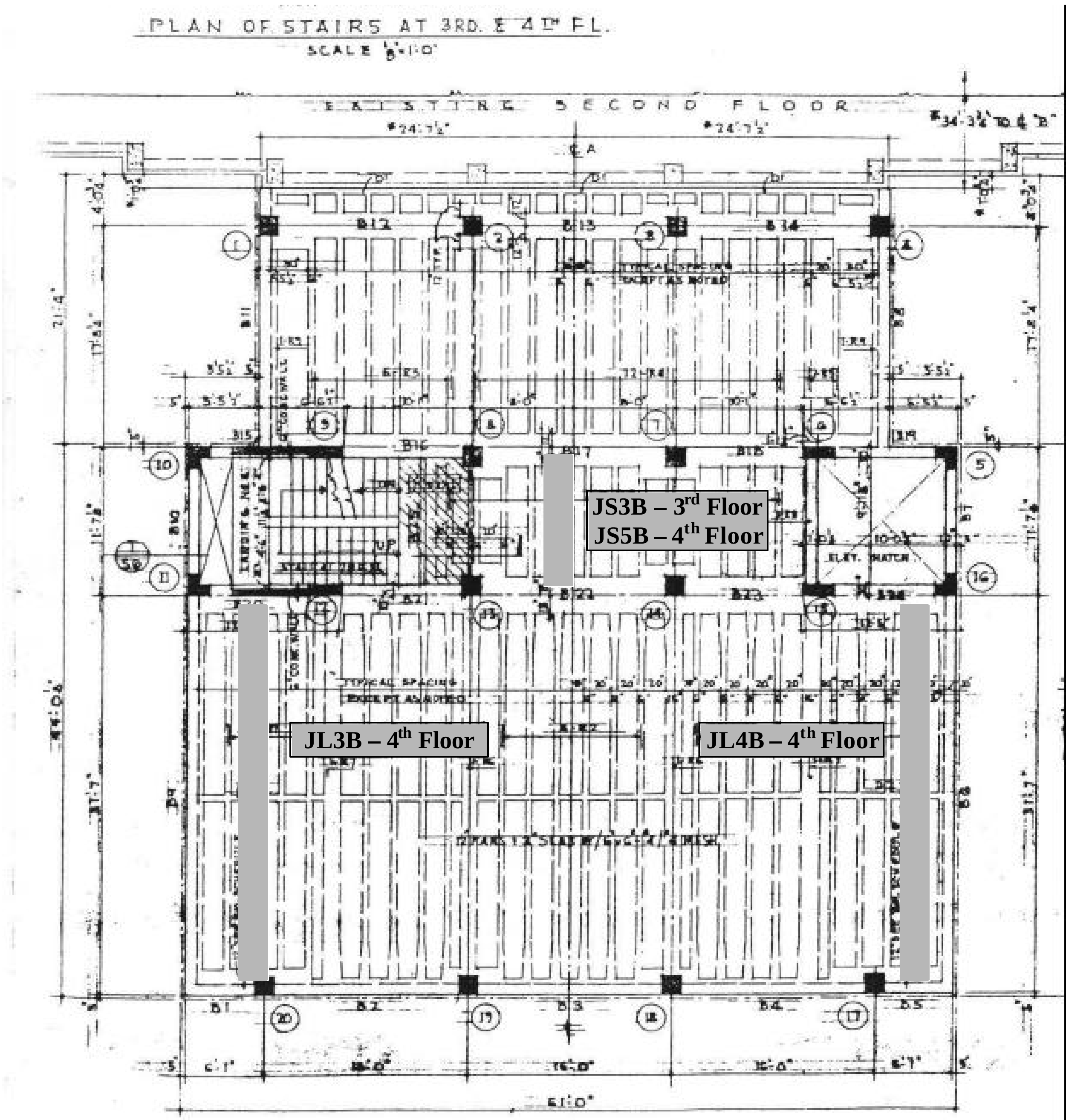

Figure A.7: Plan view shows locations of tested members

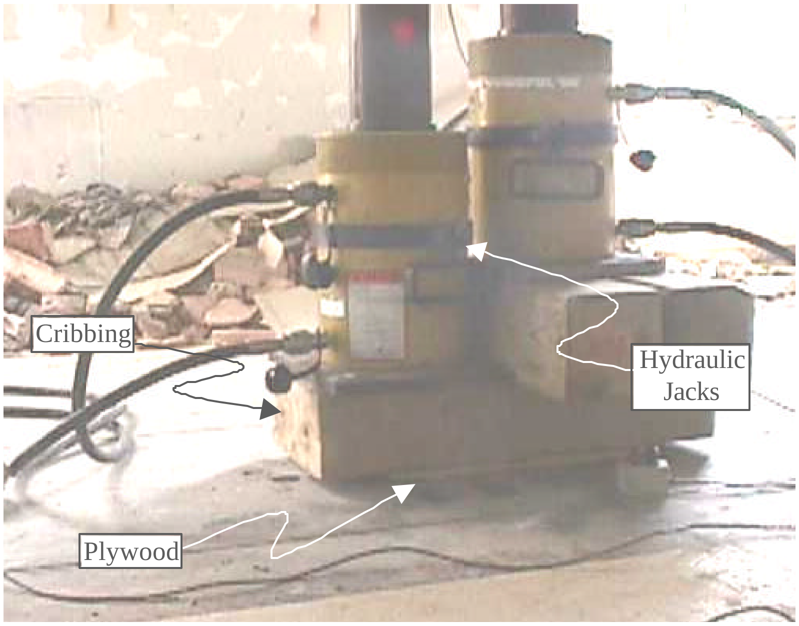

Figure A.8: Typical load setup on top of test member

Figure A.9: Typical shoring setup on the floor above the test member

Figure A.10: Typical instrumentation setup below the test member

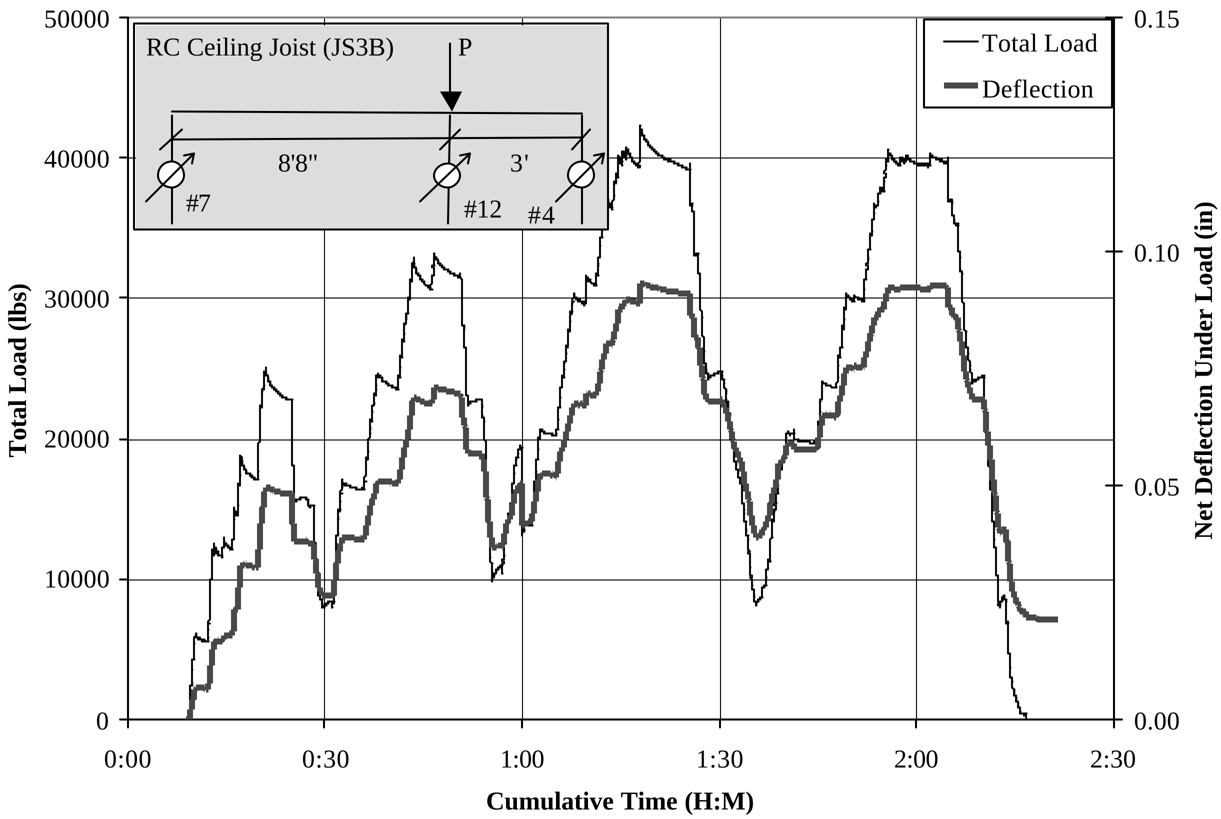

Figure A.11: Time history of rapid load test for JS3B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

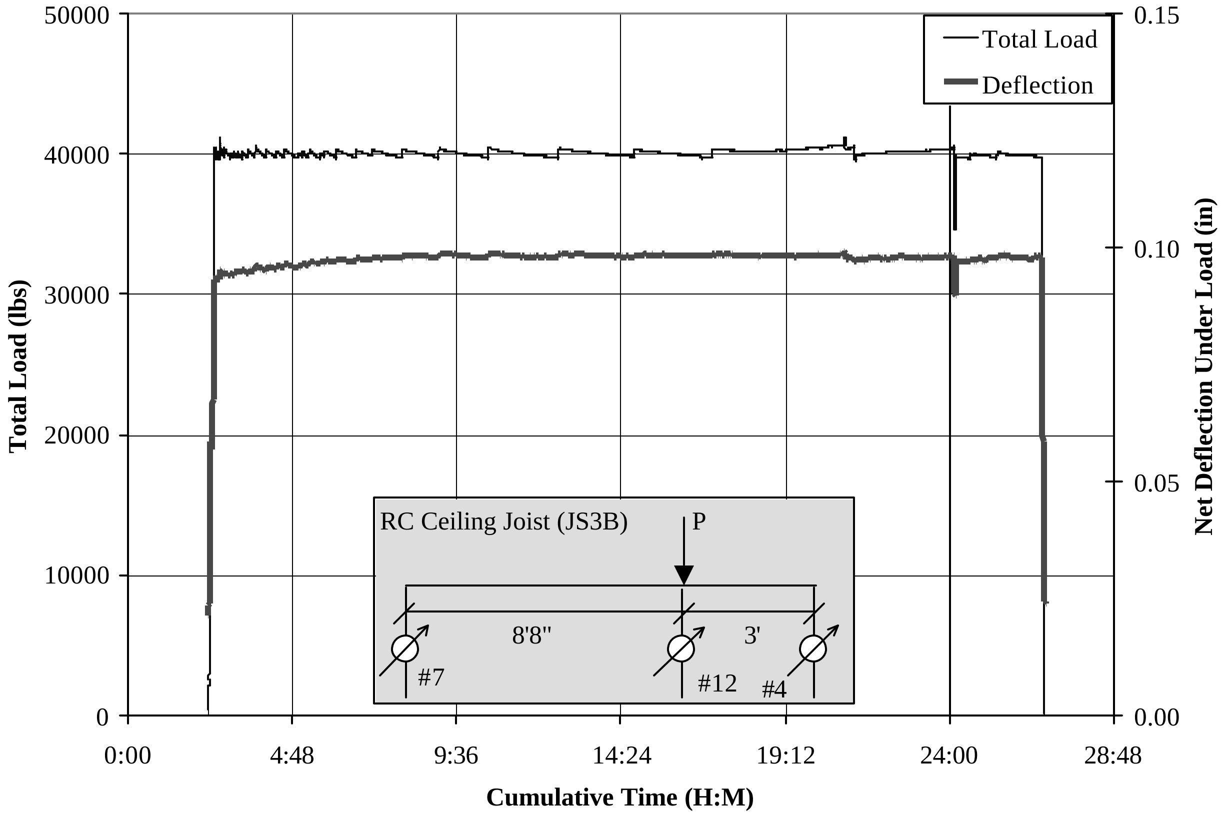

Figure A.12: Time history of 24-hour load test for JS3B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

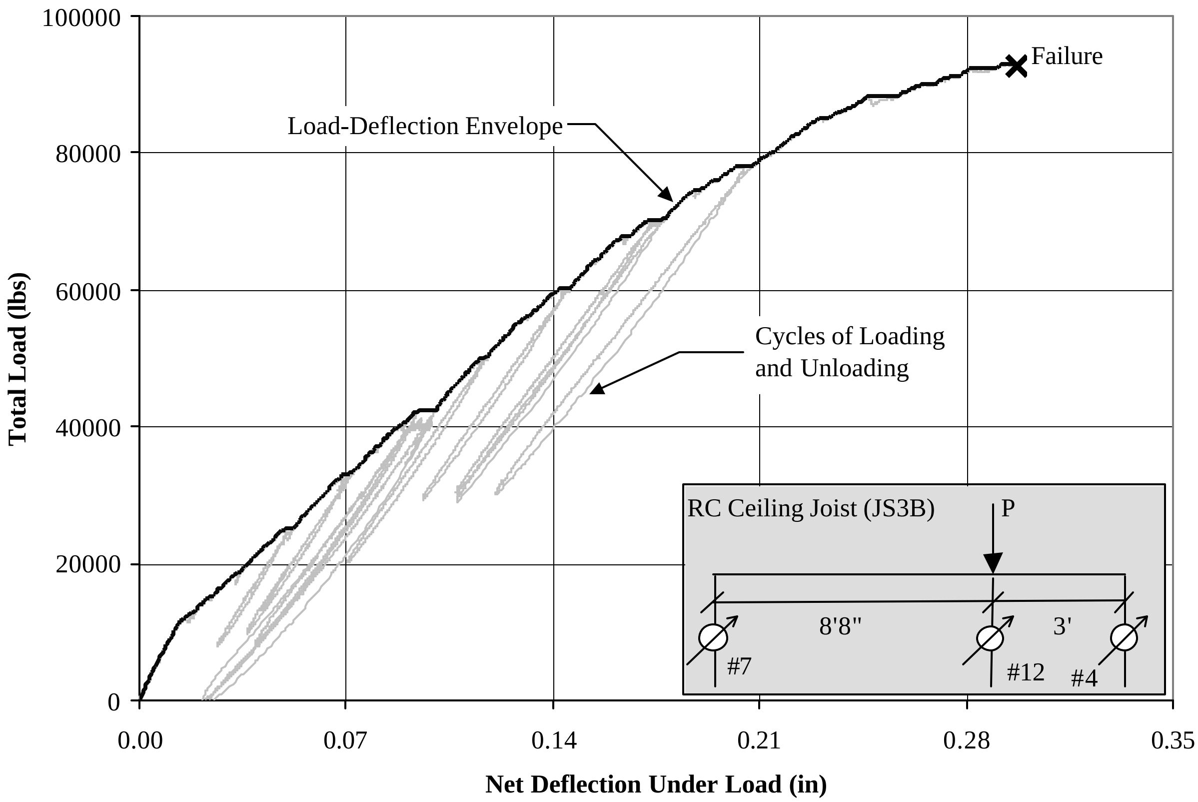

Figure A.13: Load versus deflection curve for JS3B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

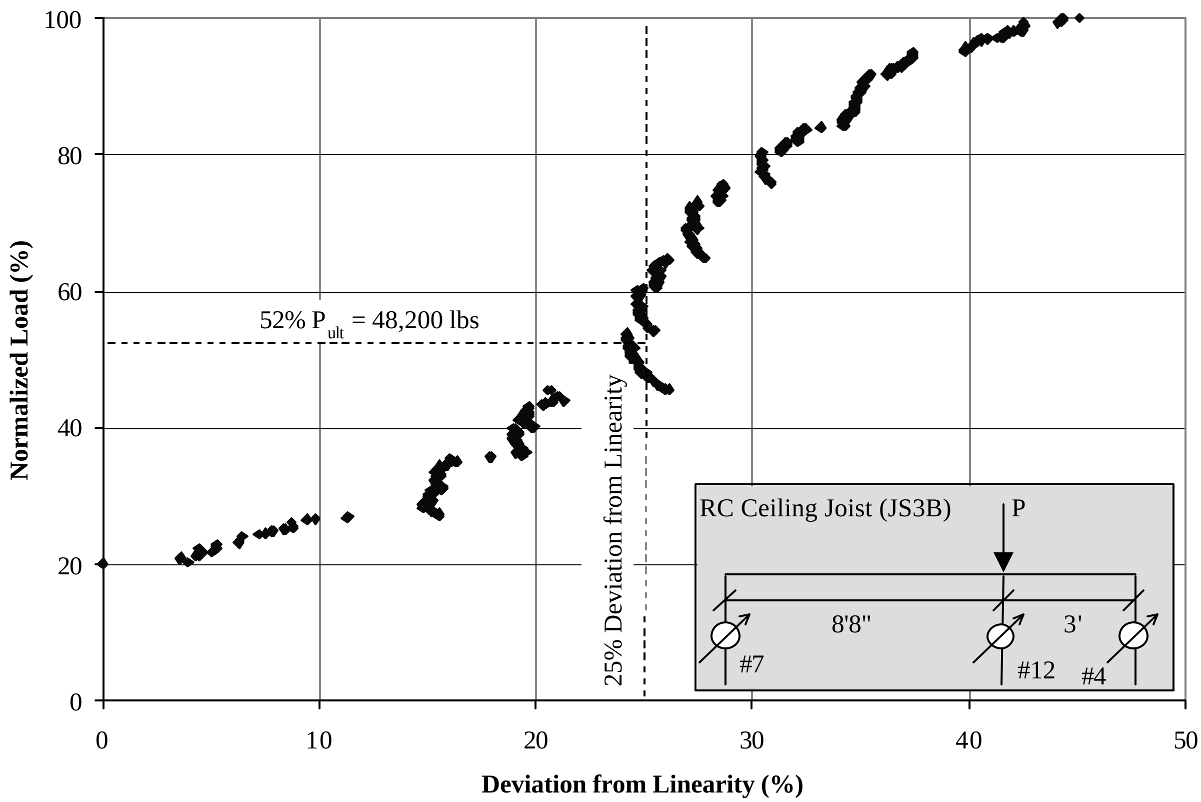

Figure A.14: Normalized load versus deviation from linearity for JS3B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

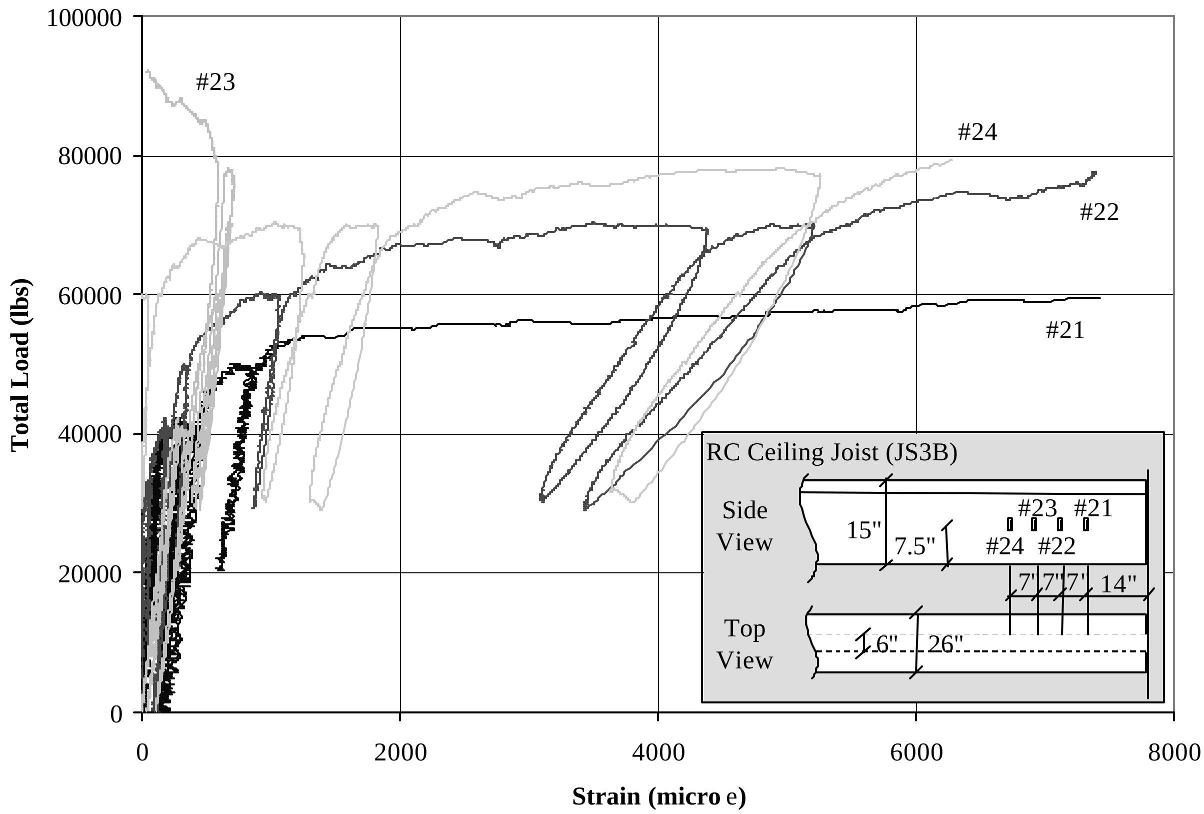

Figure A.15: Load versus strain for JS3B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

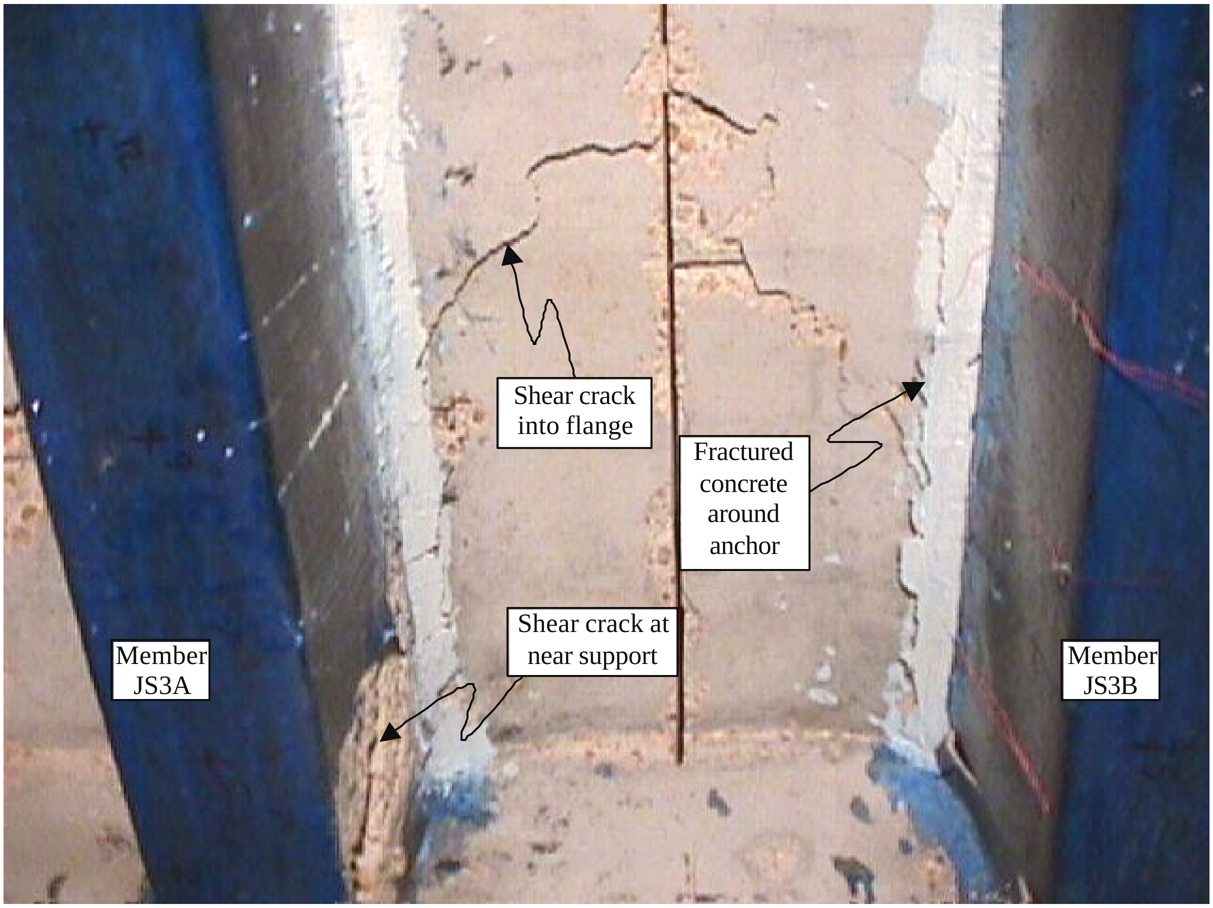

Figure A.16: Failure of members JS3A and JS3B

Case Study #3: Short Span Ceiling Joist (JS5B)

Joist JS5B had two plies of externally bonded FRP shear reinforcement as compared to only one ply for JS3B (Raghu, 1999).

Figure A.17 is a time history of the load and net deflection for the rapid load test, and Figure A.18 is the same for the 24-hour load test. As shown on Figure A.17, the fourth cycle achieved the average maximum load of the third cycle (i.e., 40,000 lbs. (178 kN)) at the same deflection (i.e., 0.06 in (1.5 mm)). The repeatability, calculated as described in Section 3.2, was greater than 100%. The net deflection achieved in the 24-hour test (Figure A.18) was similar to that under the same load during the rapid load test.

Permanency values calculated for the third and fourth cycles of the rapid load test are 11% and 2%, respectively. These low levels of permanency, as well as the decrease in the permanency with repetition, help show that the member is capable of safely maintaining that applied load.

Figure A.19 shows the load versus net deflection curve for the joist up to failure. The failure load, P_{ult}, was approximately 90,700 lbs. (403 kN) at a net deflection of 0.22 in. (5.6 mm).

The maximum load level attained in the rapid and 24-hour load tests (approximately 45% of the true capacity of the member) correlates to a maximum deviation from linearity of about 21%.

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The level of load that was required to achieve a 25% deviation from linearity was approximately 52%P_{ult} (i.e., 47,000 lbs. (209 kN)).

During the test to failure, a significant increase in strain did not occur until the load level of approximately 48,000 lbs. (214 kN). Below this load level, the joist showed a linear elastic behavior, which suggests that the concrete may not have developed shear cracks.

The failure mode for JS5B was very similar to that of JS3B.

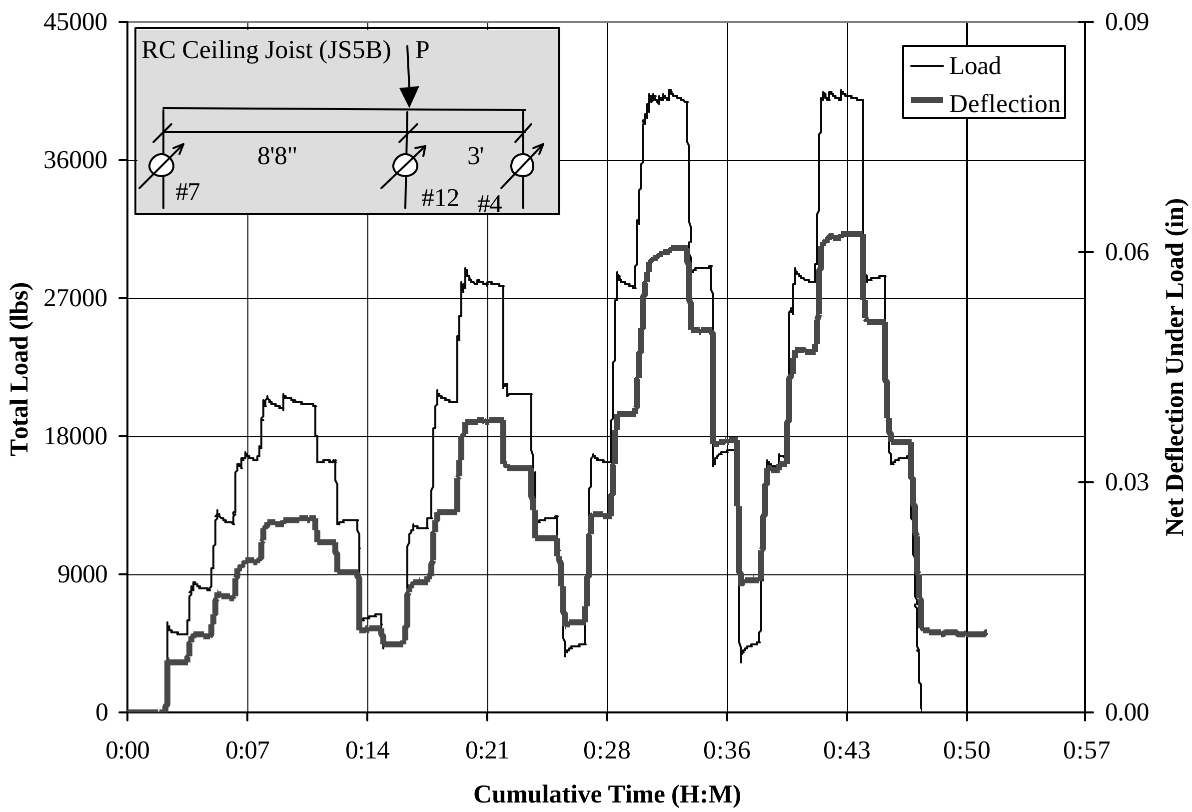

Figure A.17: Time history of rapid load test for JS5B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

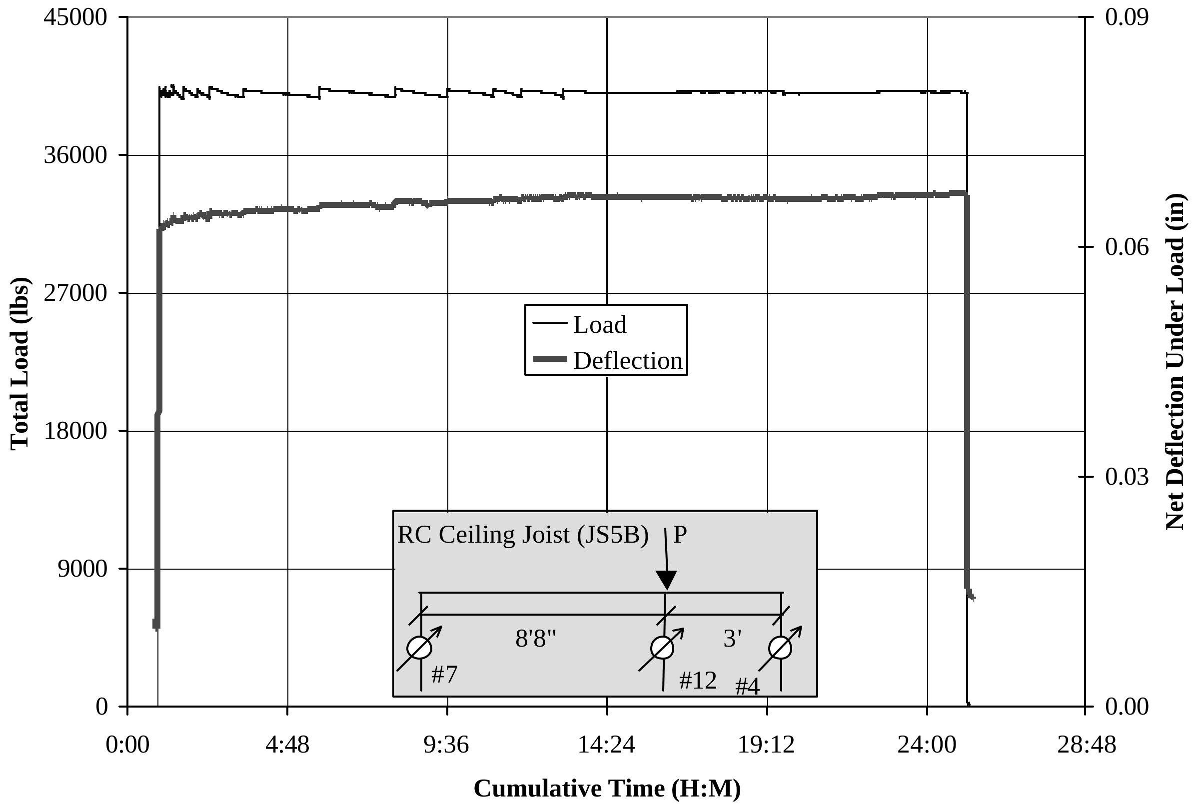

Figure A.18: Time history of 24-hour load test for JS5B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

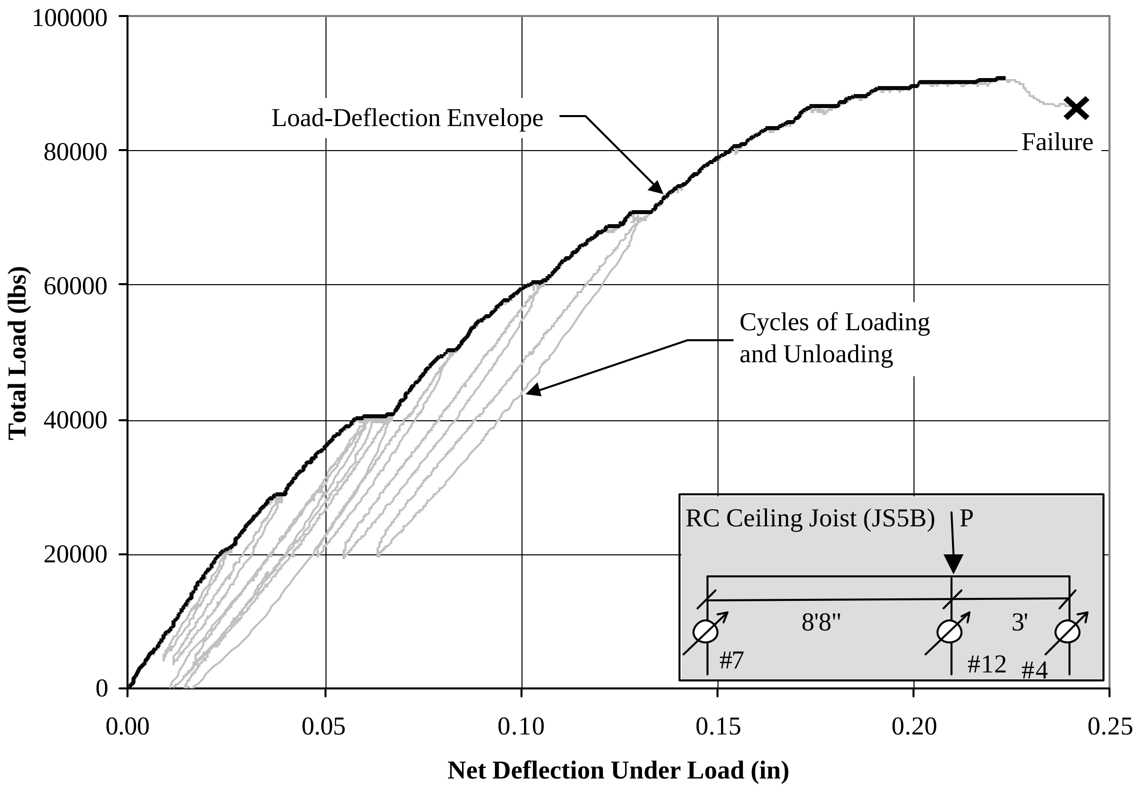

Figure A.19: Load versus deflection curve for JS5B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

Case Study #4: Long Span Ceiling Joist (JL3B)

JL3B was a long joist with one ply of externally bonded FRP shear reinforcement without an end anchor (Khalifa, et al., 1999 and Raghu, 1999).

Figure A.20 is a time history of the load and net deflection for the rapid load test, and Figure A.21 is the same for the 24-hour load test. As shown on Figure A.20, the rapid load test was conducted using three pairs of repeated load cycles. The sixth cycle achieved the average maximum load of the fifth cycle (i.e., 12,000 lbs. (53.4 kN)) at the same deflection (i.e., 0.08 in (2.0 mm)). The repeatability, calculated as described in Section 3.2, was greater than 100% for all three pairs of load cycles. The net deflection achieved in the 24-hour test (Figure A.21) was similar to that under the same load during the rapid load test. The variation in recorded deflection readings during the 24-hour test may be attributed to the changes in temperature.

Permanency values for the rapid load test are 19% for the first cycle, 0% for the second, 10% for the third, 1% for the fourth, 8% for the fifth, and 3% for the sixth. These levels of permanency, as well as the decrease in the permanency with repetition, help show that the member is capable of safely maintaining that applied load.

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Figure A.22 shows the load versus net deflection curve for the joist up to failure. The failure load, P_{ult}, was approximately 70,800 lbs. (315 kN). The net deflection under the ultimate load was 1.7 in. (43 mm) and the maximum net deflection was approximately 1.9 in. (48 mm).

The maximum load level attained in the rapid load test (approximately 17% of the true capacity of the member) correlates to a maximum deviation from linearity of about 20%. The level of load that was required to achieve a 25% deviation from linearity was approximately 27%P_{ult} (i.e., 19,200 lbs. (85 kN)).

During the test to failure, a significant increase in strain did not occur until the load level of approximately 30,000 lbs. (133 kN). Below this load level, the joist showed a linear elastic behavior, which suggests that the concrete may not have developed shear cracks.

A combination of negative flexure and peeling of the FRP shear reinforcement controlled the failure of JL3B.

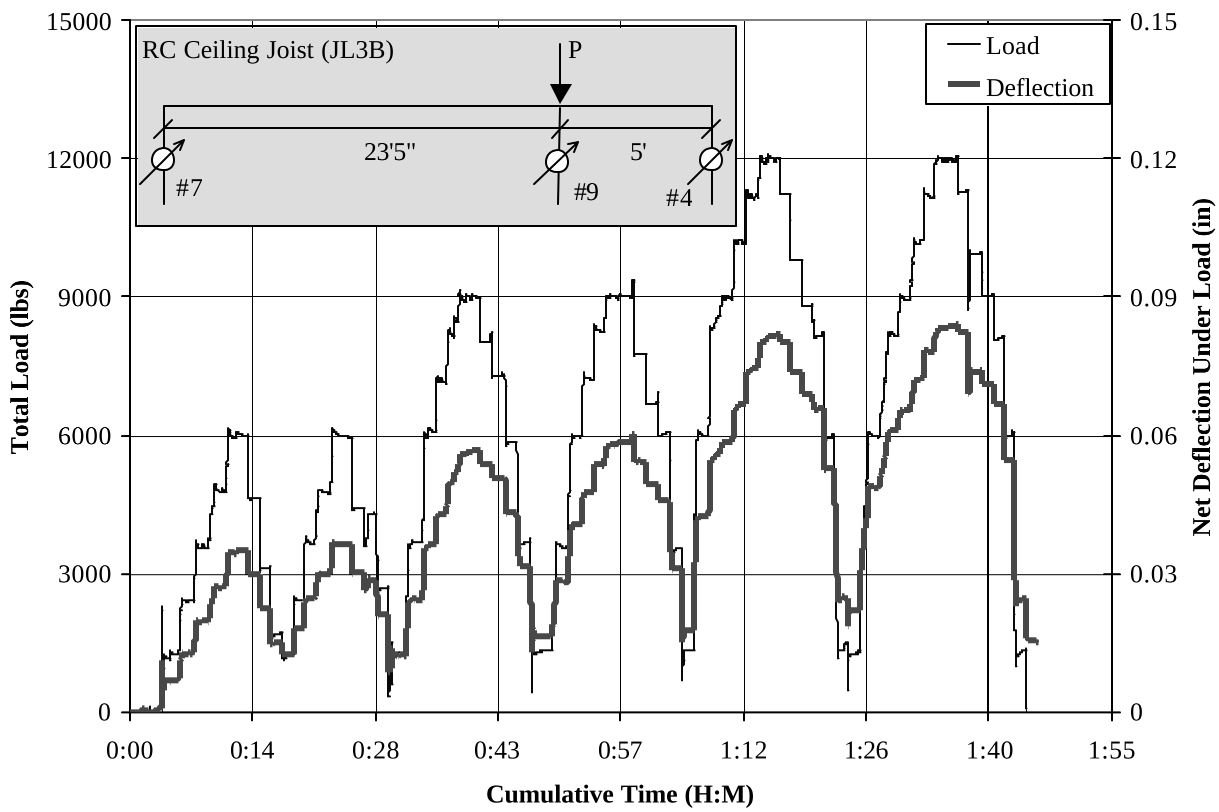

Figure A.20: Time history of rapid load test for JL3B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

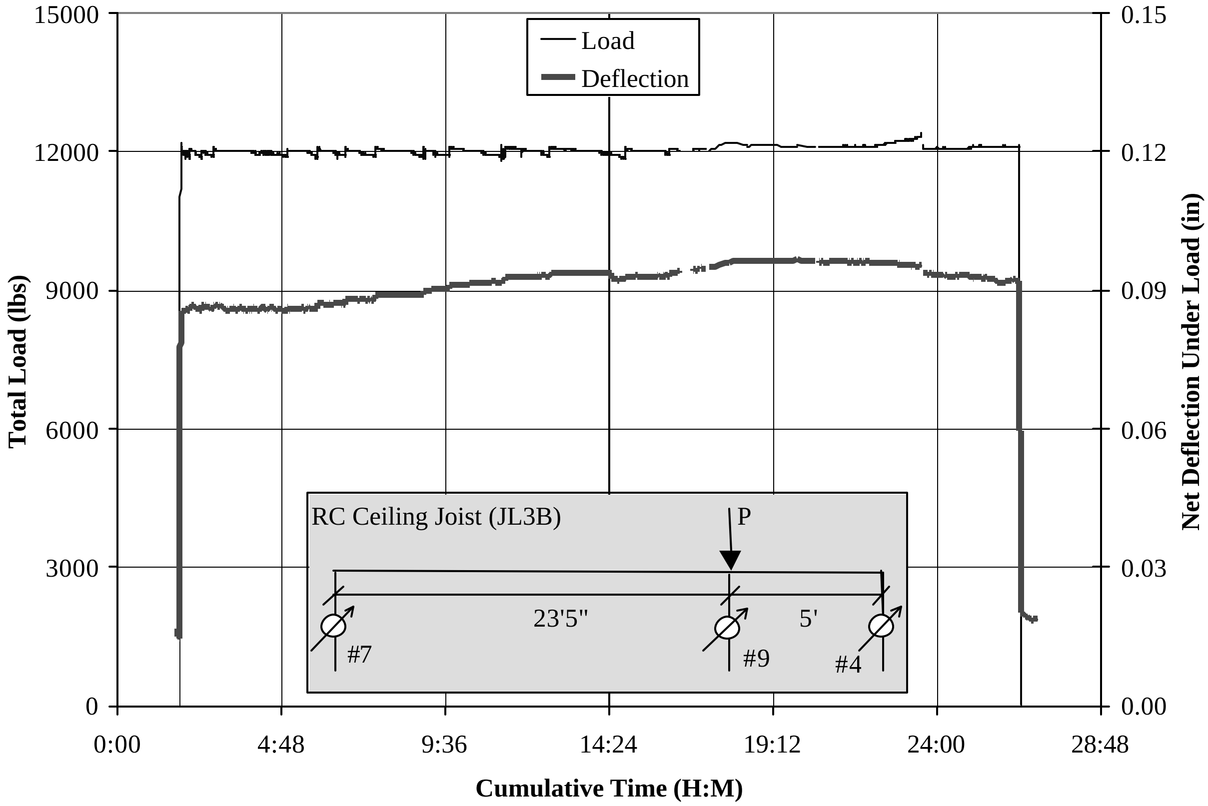

Figure A.21: Time history of 24-hour load test for JL3B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

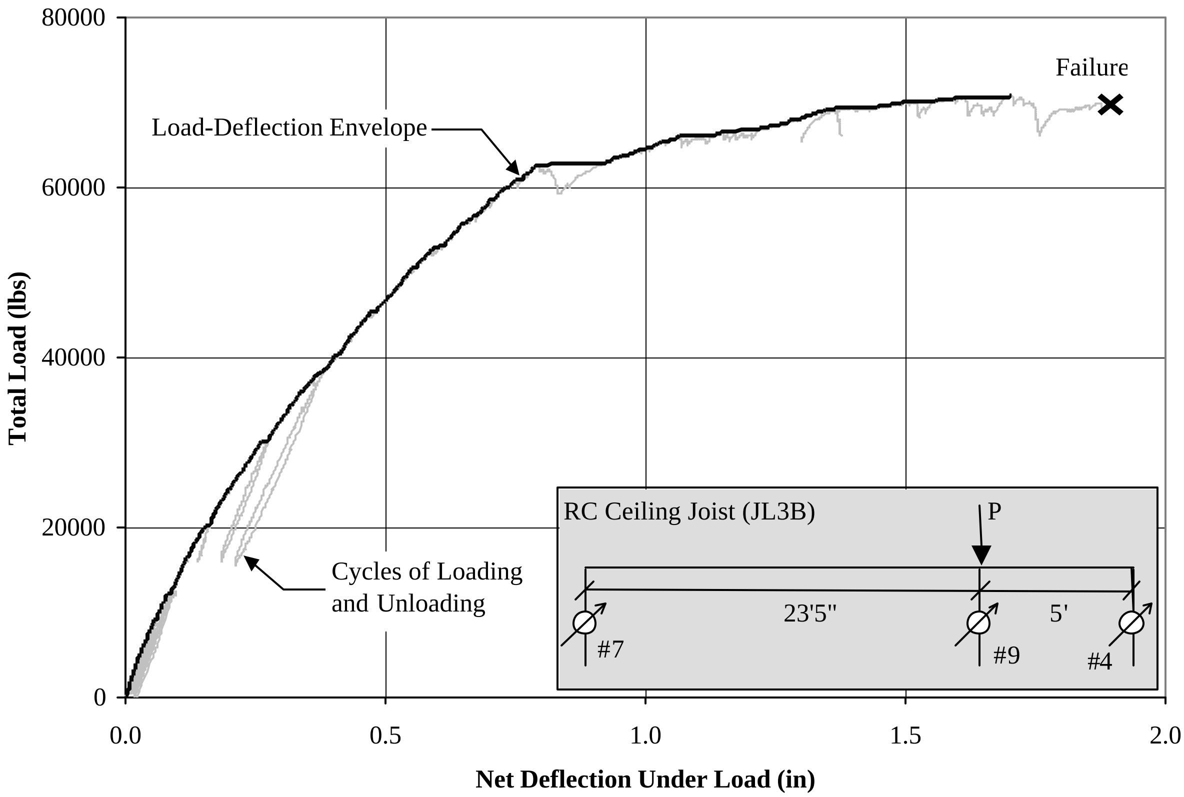

Figure A.22: Load versus deflection curve for JL3B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

Case Study #5: Long Span Ceiling Joist (JL4B)

The strengthening of JL4B was similar that of JL3B except JL4B had the end anchor for the externally bonded FRP shear reinforcement (Khalifa, et al., 1999 and Raghu, 1999).

Figure A.23 is a time history of the load and net deflection for the rapid load test, and Figure A.24 is the same for the 24-hour load test. As shown on Figure A.23, the rapid load test was conducted using three pairs of repeated load cycles. The sixth cycle achieved the average maximum load of the fifth cycle (i.e., 22,200 lbs. (98.8 kN)) at the same deflection (i.e., 0.27 in (6.9 mm)). The repeatability, calculated as described in Section 3.2, was greater than 100% for all three pairs of load cycles. The net deflection achieved in the 24-hour test (Figure A.24) was similar to that under the same load during the rapid load test. The variation in recorded deflection readings during the 24-hour test may be attributed to the changes in temperature.

Permanency values for the rapid load test are 32% for the first cycle, 5% for the second, 10% for the third, 3% for the fourth, 11% for the fifth, and 2% for the sixth. These levels of permanency, as well as the decrease in the permanency with repetition, help show that the member is capable of safely maintaining that applied load.

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Figure A.25 shows the load versus net deflection curve for the joist up to failure. The failure load, P_{ult}, was approximately 65,200 lbs. (315 kN). The net deflection under the ultimate load was 1.7 in. (43 mm) and the maximum net deflection was approximately 1.9 in. (48 mm).

The maximum load level attained in the rapid load test (approximately 35% of the true capacity of the member) correlates to a maximum deviation from linearity of about 24%. The level of load that was required to achieve a 25% deviation from linearity was approximately 41%P_{ult} (i.e., 26,500 lbs. (118 kN)).

During the test to failure, a significant increase in strain did not occur until the load level of approximately 30,000 lbs. (133 kN). Below this load level, the joist showed a linear elastic behavior, which suggests that the concrete may not have developed shear cracks.

Negative flexure was the mode of failure for this joist.

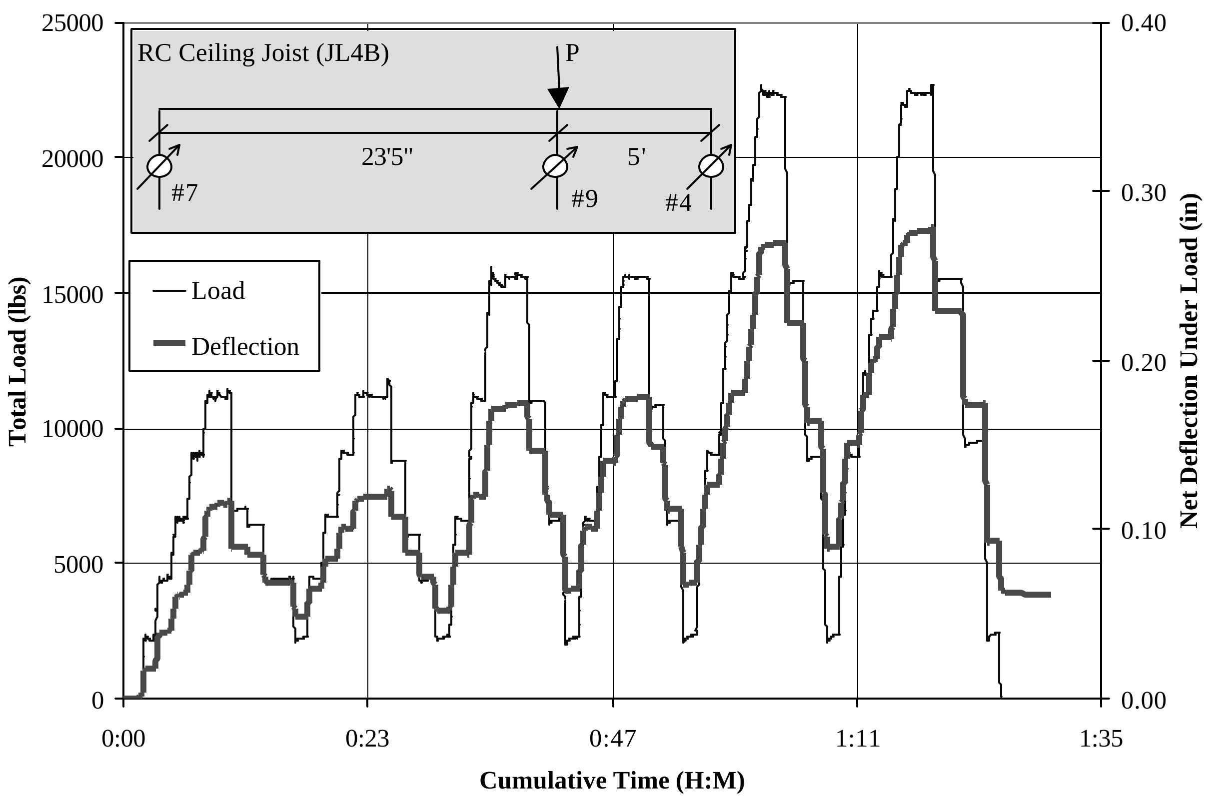

Figure A.23: Time history of rapid load test for JL4B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

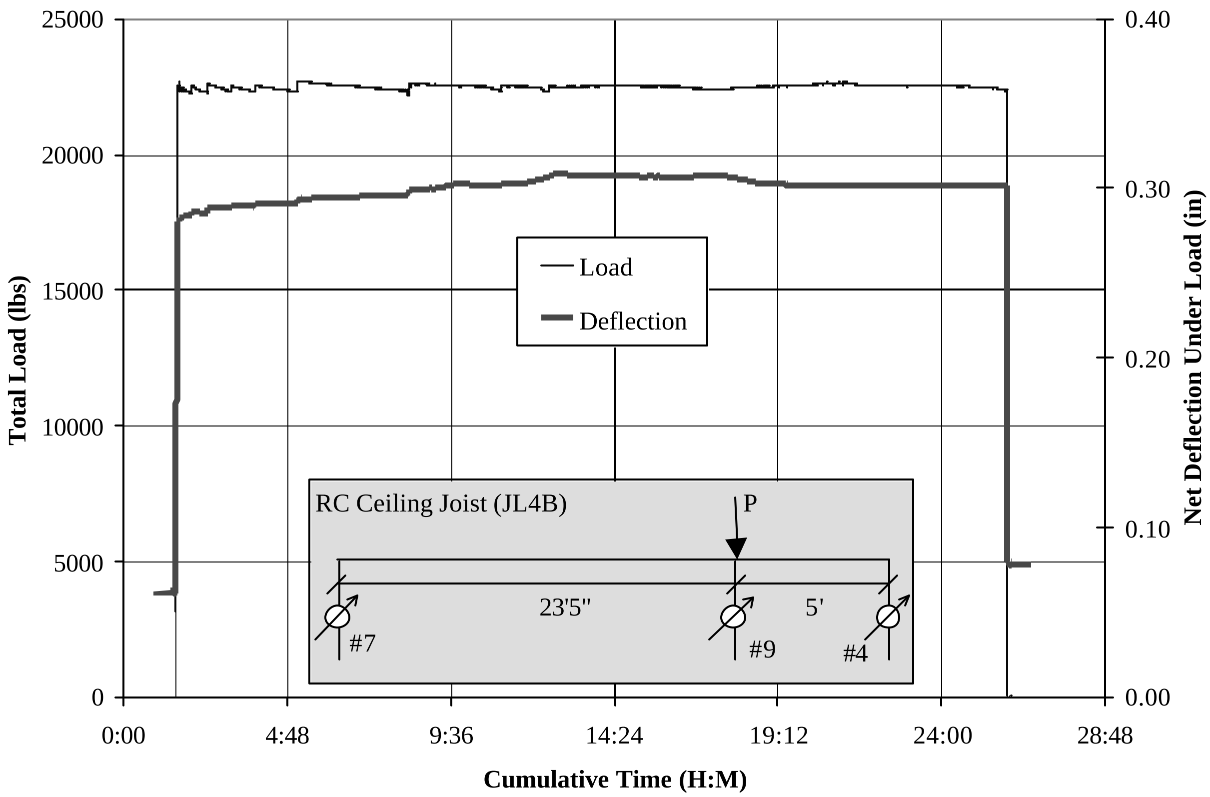

Figure A.24: Time history of 24-hour load test for JL4B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

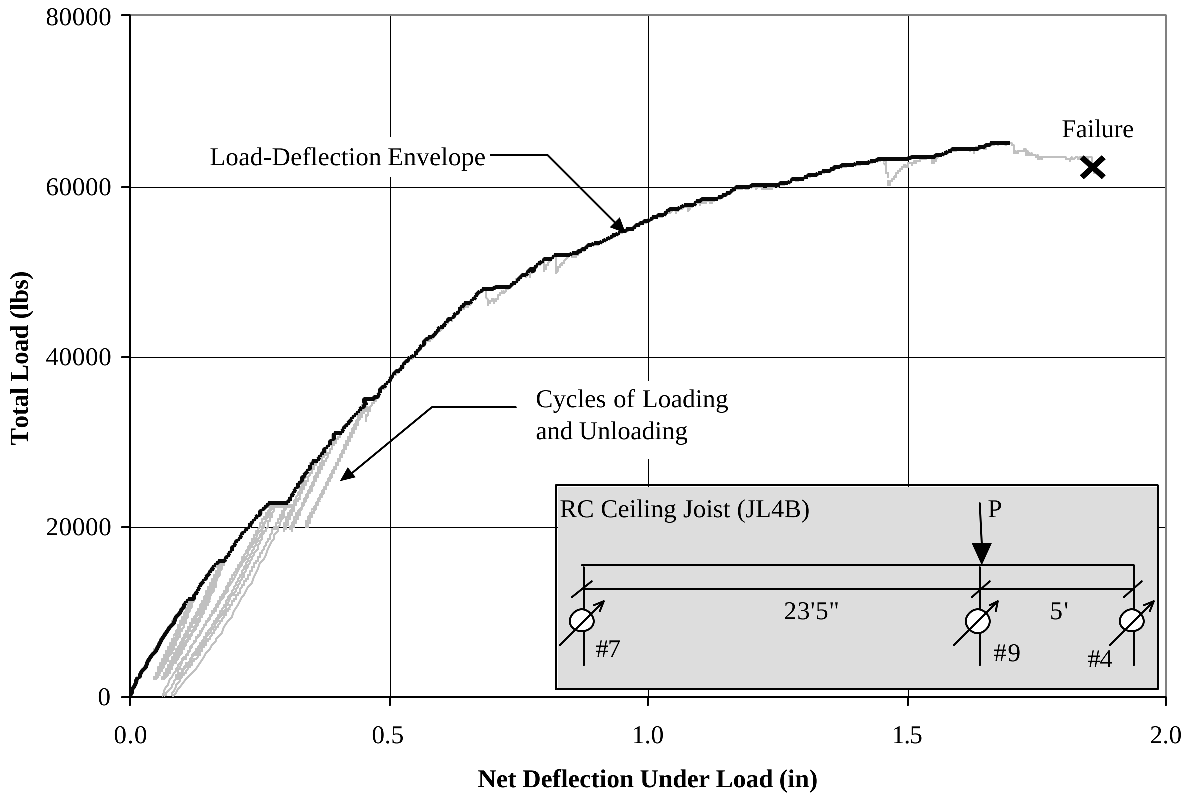

Figure A.25: Load versus deflection curve for JL4B
(1 in. = 25.4 mm, 1 lb. = 4.45 N)

APPENDIX B COMMERCIAL PROJECTS

Rapid load testing has recently been used to validate new strengthening techniques in concrete structures. The use of new materials, such as fiber reinforced polymers (FRP), which have not yet been accepted into standard practice, may lead to some questions as to their performance in the field. Rapid load testing is a simple way to verify these strengthening systems. Several "proof" load tests have been conducted, and representative ones are summarized below.

Case Study #6: Atlanta, Georgia: Push-Down

The post-tensioned PC slab of a parking garage was strengthened with gunite RC beams shortly after construction in order to correct a deficiency in the number of steel tendons along the East-West alignment of the building. The integrity of the composite action between the gunite beam and slab was to be based solely on the strength of the interfacial bond between the two. Since delamination had occurred over time, such action was compromised and epoxy injection was required. In order to find a permanent solution to the delamination problem, it was suggested that the gunite beams be demolished and replaced with externally bonded carbon FRP sheets.

Before the specialty contractor began with the commissioned CFRP strengthening work, a rapid load test assessment was carried out. In this test, one concentrated force was applied to the slab column-strip by means of hydraulic jacks (Figure B.1). The placement of the jacks and the reaction points were selected on the basis of the structure's geometry. For the case under examination, it was chosen to perform a push-down test, as described in Section 2.2.2. The hydraulic jacks reacted against the two floors above (Figure B.2). Deflection at several points (i.e., under the load, at the quarter-span sections, at the drop panel) was measured. Following repeated loading and unloading cycles, it was possible to capture the transient and permanent deformation response of the slab. The level of the maximum load was determined based on preliminary calculations and the response of the structure during the load test.

The load test was repeated with the same modality after the execution of the CFRP strengthening work. The level of maximum load was increased to provide a safety factor against service load conditions, but it was always maintained within the elastic range of the structure. Live load was removed during the strengthening and testing of the slab. By comparing the outcome of the two tests, it was possible to evaluate the effectiveness of the FRP strengthening method.

For additional information regarding the structural geometry, material properties, and levels of load involved with this case study, see Nanni and Gold (1998a), Nanni and Gold (1998b), and Nanni, et al. (1998).

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Figure B.1: Load applied by hydraulic jacks

Figure B.2: Shoring on floor above tested slab

Case Study #7: Winston-Salem, North Carolina: Push-Down

Strengthening of a two-way, post-tensioned, flat slab was necessary due to a change in its use. The strengthening was accomplished using externally bonded CFRP sheets bonded to the slab's soffit in the positive moment regions and to the top of the slab in the negative moment regions along the column lines (Gold and Nanni, 1998). The push-down test method, as described in Section 2.2.2 was used for these tests. The load was applied using a combination of sandbags and hydraulic jacks, as shown in Figure B.3. The transport box that contains the electric pump used to supply the fluid to the hydraulic jacks, as well as the externally bonded negative flexural strengthening CFRP sheets, are also shown in this figure. The shoring on the floor above the hydraulic jacks, shown in Figure B.4, and the LVDTs mounted on aluminum tripods below the test member, shown in Figure B.5, caused little disruption to the office space at the test site. The effectiveness of the CFRP strengthening was successfully demonstrated by the rapid load tests.

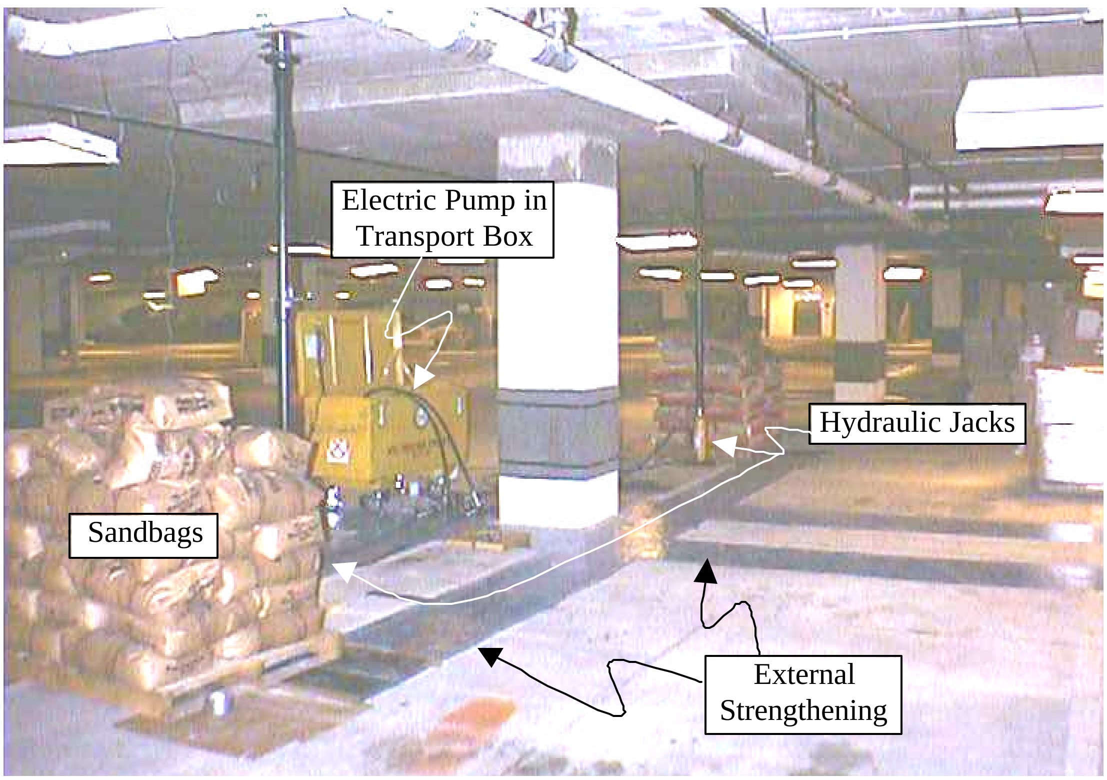

Figure B.3: Load applied using hydraulic jacks and sandbags

Figure B.4: Shoring in place for push-down method

Figure B.5: LVDTs mounted on aluminum tripods

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Case Study #8: Baltimore, Maryland: Pull-Down (Fixed)

Strengthening of an RC slab was required as a result of a change in use coupled with a lack of reinforcement in a few isolated areas of the slab. The addition of externally bonded CFRP sheets sought to make up for this deficiency in these areas. The rapid load test was used as a means of validating the design and construction of the strengthening system. The test performed was a pull-down test in which a hydraulic jack (Figure B.6), resting on the second floor, reacted against chains (Figure B.7) pulling on the first floor columns (Figure B.8), as described in Section 2.2.2. The use of hydraulic jacks allowed for easy manipulation of the load, and since the jack applied a concentrated load, it was possible to focus the test only on those areas in which a deficiency was corrected. The repaired slab was loaded to 85% of its ultimate design capacity by using progressively increasing load cycles and steps. The test was completed in 6 hours including setting up and removing the test equipment. A combination of deflection and strain measurements taken during the load test and a finite element analysis were conducted upon completion of the test.

The rapid load test did not seek to evaluate the safety of the entire structural system. Rather the test was designed to prove the performance of the strengthening system and verify the positive bending moment capacity at the mid-span of the slab between two columns. This was achieved by loading the structure and measuring strains in the concrete and strengthening materials. These strains were related to the material stresses, and these stresses were correlated with the assumed stress levels in the design of the strengthening system.

Geometry, including column locations and member sizes, was determined mostly from the original architectural drawings. The column locations were field verified prior to testing. The slab of interest, 6.5 in. (165 mm) thick, is continuous along three edges and supported by an edge beam along the fourth edge. Positive flexural reinforcement consists of #3 (9.5-mm diameter) bars spaced at 9 in. (229 mm). It was assumed that 0.75 in. (19 mm) of clear cover was provided for this reinforcement. Strengthening was achieved with a 20 in. (508 mm) wide by 9.5 ft. (2.90 m) long externally bonded FRP laminate located on the soffit of the slab.

The material characteristics were determined from the original design specifications. Specifications indicated a nominal concrete strength of 3,000 psi (20.7 MPa) for the elevated slab and columns, and a minimum yield strength for the steel reinforcement of 40 ksi (276 MPa). Additionally, the supplemental FRP reinforcement has a tensile modulus of 33 Msi (228 GPa) and a rupture strength of 505 ksi (3,482 MPa) according to the manufacturer's specifications.

A service dead load of 81.25 psf (3.89 kN/m^2) results only from the self-weight of the slab. The service live load for the area of interest is 100 psf (4.79 kN/m^2). The maximum test load was determined from these values assuming an additional dead load in place of 5 psf (0.24 kN/m^2) due to furniture, flooring, and partitions.

Evidence of the structural integrity was displayed in the load versus deflection curve and the moment versus strain curve, as they showed a linear response up to the maximum test load. In addition, no significant residual deflections were recorded. The magnitudes of the measured strains were low, and corresponded to those expected from an uncracked section analysis. Additional evidence that the structure was uncracked was seen in the deflection readings. The structure behaved exactly as a linearly elastic plate with an elastic modulus of 3.4 ksi (23.4 GPa). It was concluded that the full 6.5 in. (165 mm) of thickness was effective under the loads applied, and it remained uncracked under a bending moment equivalent to a moment produced by 85% of the factored load condition. The structure safely carried the moments induced during testing and thus will safely carry the desired design loads.

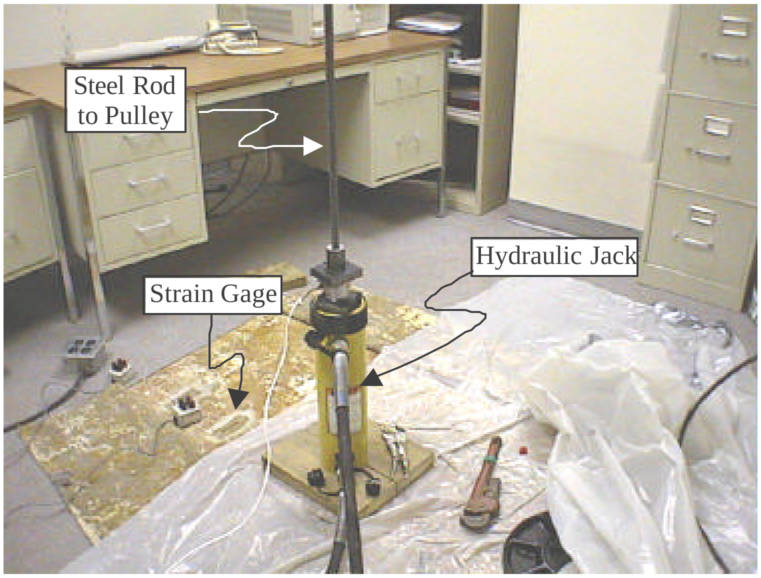

Figure B.6: Hydraulic jack used to apply load

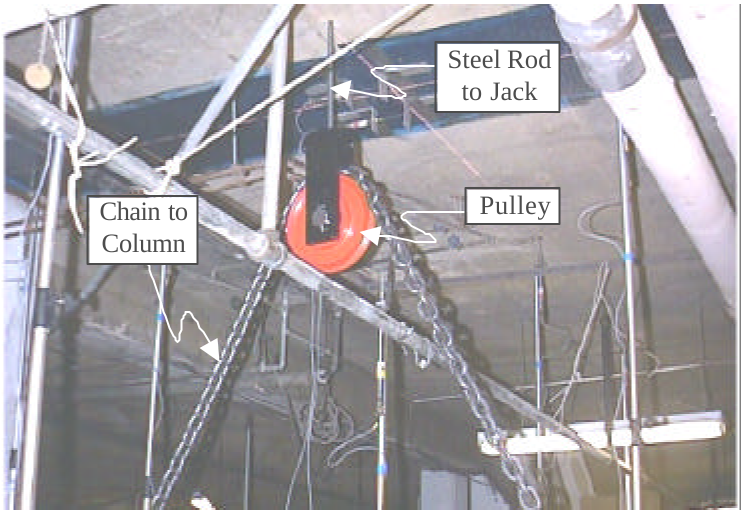

Figure B.7: Apparatus for providing reaction for hydraulic jacks

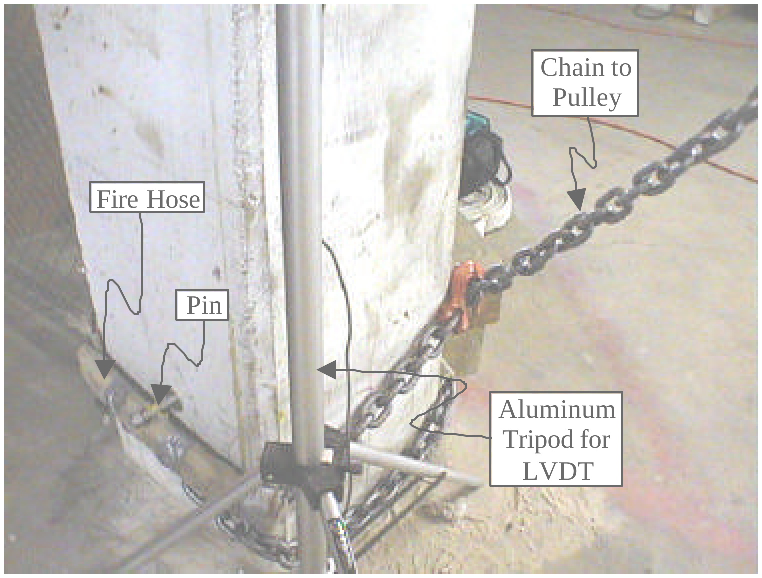

Figure B.8: Detail showing reaction provided by the column

Case Study #9: Perugia, Italy: Pull-Down (Mobile)

A doubly curved, precast, PC shell was strengthened with externally bonded CFRP laminates. The shell was part of the roof of an industrial building and had experienced severe localized damage due to accidental heat radiating from a flue (Barboni, et al., 1997 and Benedetti and Nanni, 1998). Because of the uncertain prestress loss and with the motivation of checking the efficiency of the CFRP strengthening, a load test program was conducted to compare the PC shell behavior before and after the rehabilitation.

The pull-down type test with a mobile reaction, as described in Section 2.2.2, was used in this load test program. A concentrated force was applied at the middle of the PC shell and the deflections at three points (i.e., under the load, at the quarter section, and the supported end) were measured using LVDTs. Figure B.9 shows a detail of the spreader beam used to apply the load to the PC shell. A steel cable, shown in Figure B.10, passed through the PC shell and was connected to a hydraulic jack, which reacted against the dead weight of a forklift in order to apply the load. In the post-strengthening test, LVDTs were used to record the strain of the longitudinal and transverse CFRP strips. Attention was focused on the mid- and quarter-span vertical displacements. Following repeated loading and unloading cycles with increasing loads, it was possible to determine parameters such as residual deformation, repeatability, linearity, and energy dissipated for each cycle.

Prior to the start of the repair work, the load test was conducted with a maximum applied load of 2,700 lbs. (12 kN). The test was limited to this load level (one third of the target value) in order to prevent any additional damage to the shell. The precaution was motivated by the following considerations: a desire to maintain low stress in the weakened portion of the tendons, observation of an excessive quarter-to-mid-span deflection ratio (i.e., 0.84), and observation of a relatively high mid-span deflection, 0.386 in. (9.8 mm). The typical assumption that a roof structure subjected to service load can safely experience a deflection in the order of L/200 (where L is the span) may not be acceptable in the case of a PC shell. In fact, for the shell under consideration, this would correspond to a concrete compressive stress of 2,320 psi (16 MPa) in addition to that already present.

During the second test (after repair), aiming to reproduce the service condition of the roof, the target load of 8090 lbs. (36 kN) was imposed. For the load level of 2,700 lbs. (12 kN), the deflections before and after strengthening were 0.386 in. (9.8mm) and 0.303 in. (7.7 mm), respectively.

Important information can be extracted from the quarter-to-mid-span deflection ratio. For a simply supported beam in the linear-elastic range and under a concentrated central load, this deflection ratio is theoretically equal 0.6875. Examining the experimental ratios obtained in the two tests, values of 0.84 and 0.70 were computed for the pre- and post-strengthening tests, respectively. Also, it was noted that, although the load was three times higher in the second test, the first test showed a larger dissipated energy ratio. In fact, the inelastic deformation of the damaged zone can be considered as the primary mechanism of energy absorption. It was concluded that the localized damage affected the load-deflection behavior of the shell and that the implemented repair method corrected the loss of flexural/shear stiffness.

In order to confirm the validity of the experimental results, a numerical analysis was performed using the finite element (FE) method. It was found that the loss of stiffness corresponding to the experimental quarter-to-mid-span deflection ratio determined in the pre-strengthening test corresponded to a flexural stiffness (i.e., combined elastic modulus and moment of inertia) reduction of ten times at the location of the damage. Furthermore, the FE linear elastic analysis of the repaired PC shell based on the elastic properties obtained through direct evaluation at the site, showed deflection values in very good agreement with the ones obtained in the post-strengthening test.

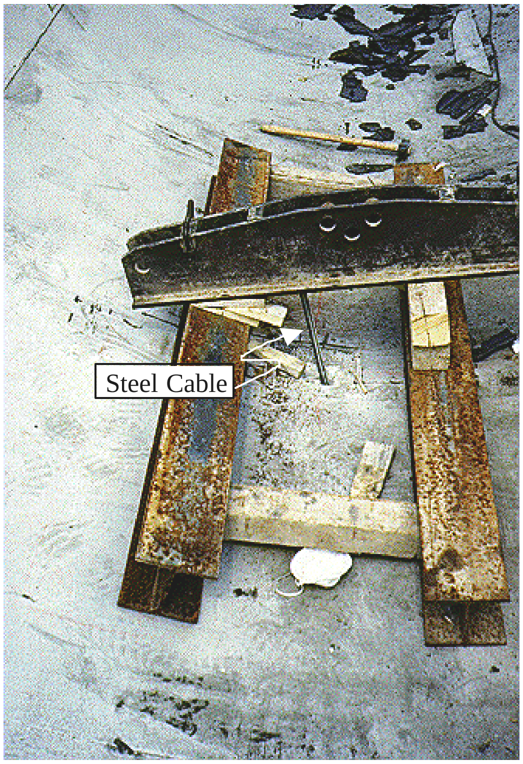

Figure B.9: Spreader beam used to apply the load

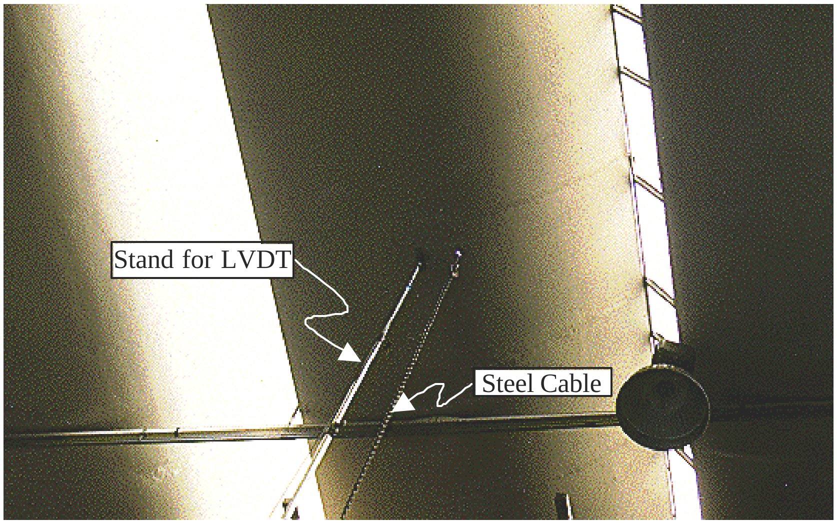

Figure B.10: Chain connecting the spreader beam to the hydraulic cylinder

Case Study #10: Oklahoma City, Oklahoma: Closed Loop

This case study describes the rapid load tests performed on the structural street level floor of a convention center. The floor required strengthening in order to increase its live load bearing capacity. The strengthening system implemented included a combination of externally bonded steel plates and CFRP sheets. The strengthening system sought to address both flexural and shear deficiencies (Hogue, et al., 1999a and Hogue, et al., 1999b).

The rapid load tests sought to evaluate end and mid-span moment capacities of a typical joist. The rapid load test demonstrated the strengthening system's ability to carry the new design loads without premature failure (i.e., debonding and concrete cover delamination).

Two load tests were performed, each using two loading configurations. The test matrix is summarized in Table B.1. The load tests concentrated on an evaluation of one joist in a structural bay. The first set of tests was performed before the strengthening system was installed. The second set of tests was performed after the strengthening system had been installed in the tested bay.

Table B.1: Summary of load test matrix

Load Test Number	Response Tested	Condition of Element
A-1	Positive moment at mid-span of a typical joist	Unstrengthened
A-2	Negative moment of a typical joist at the beam-joist intersection	Unstrengthened
B-1	Positive moment at mid-span of a typical joist	Strengthened with 4 – 4" plies of CFRP on each side of the joist stem
B-2	Negative moment of a typical joist at the beam-joist intersection	Strengthened with an A36 steel plate (1/4"x 4") bonded to the top of the joist

(1 in. = 25.4 mm)

The placement of loads and instruments for Load Configuration 1 was designed to simulate the positive moment that would be caused by a uniformly distributed load at the mid-span of a typical joist. To this end, the closed loop test method (Section 2.2.2) was used, where one hydraulic jack was located on top of the joist at mid-span and reacted against spreader beams below the joist as shown in Figure B.11.

Strain measurements were taken on the top of the slab and at various depths along the joist. A strain gage bonded to the top of the slab was used to directly measure compressive strain. An LVDT was mounted on the side of the joist with angle brackets to measure elongation over a 4.25 in. (108 mm) length, as shown in Figure B.12. This device was located at a depth of 12.75 in. (324 mm) from the top of the slab. An extensometer measured elongation at a depth of 21 in. (533 mm) from the top of the slab. The LVDT measuring elongation and the extensometer both bridged a vertical crack at mid-span of the joist. It was, therefore, possible to monitor the crack opening at this location. After the installation of the FRP, the extensometer measured elongation of the FRP laminate directly over the crack. LVDTs were also positioned along the length of the member to measure deflections before and after strengthening.

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By comparing the load versus deflection curves before and after strengthening (Figure B.13), an increase in stiffness is noticeable due to the presence of the FRP. A significant change in the width of the monitored crack was also expected. The original post-tensioned structure had little bonded reinforcement. After strengthening, the FRP sheets provided a significantly higher amount of bonded reinforcement and smeared the tensile strains over a much larger length. This type of behavior was verified with the test data. A comparison of the crack width opening for the unstrengthened and strengthened joist is shown in Figure B.14.

The placement of loads and instruments for Load Configuration 2 was designed to simulate the negative moment at the intersection of a typical joist and edge beam that would be caused by a uniformly distributed load. To this end, the closed loop test method (Section 2.2.2) was again used, in which two hydraulic jacks, located on top of the joist on either side of the edge beam, reacted against spreader beams below the joist, as shown in Figure B.15. LVDTs were again positioned along the length of the member to measure deflections before and after strengthening. No change in stiffness was noticed, and because there were no visible existing cracks in the test member, monitoring of crack widths was not undertaken.

All four rapid load tests involved applying several load cycles. Each load cycle consisted of loading the structure in steps. A minimum of four, approximately equal, load steps were used to load the structure followed by at least two steps to unload the structure. Each load step was maintained for at least 2 minutes. During this time the mid-span deflection of the structure was monitored for stability. The peak load for each successive cycle was gradually increased to approach the maximum test load.

Moments in excess of 85% of the factored design moments were simulated in the joist. The structure showed a linear response to loading for all load levels and load configurations, indicating that the structure safely carried the moments simulated during testing.

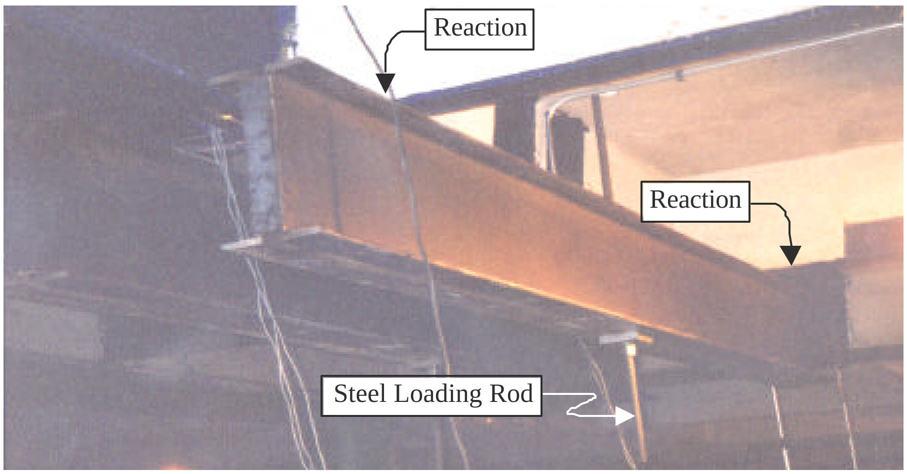

Figure B.11: Loading apparatus used for Load Configuration 1

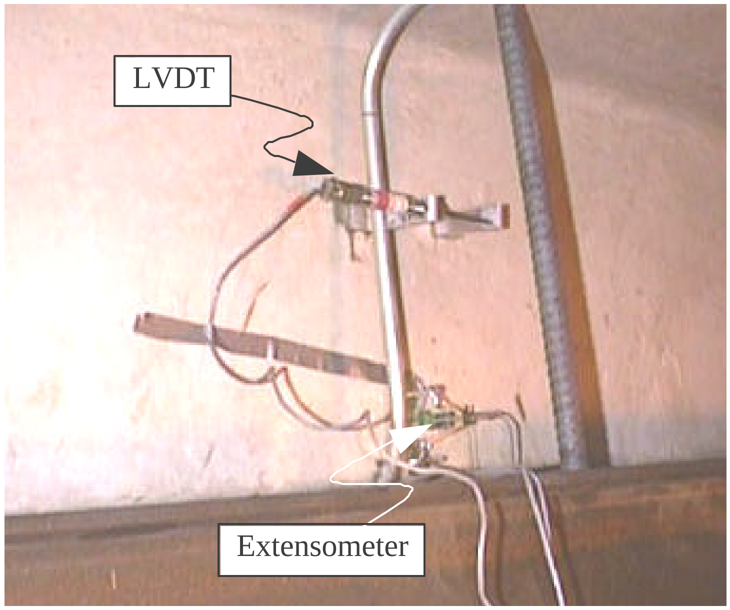

Figure B.12: LVDT and extensometer measuring elongation

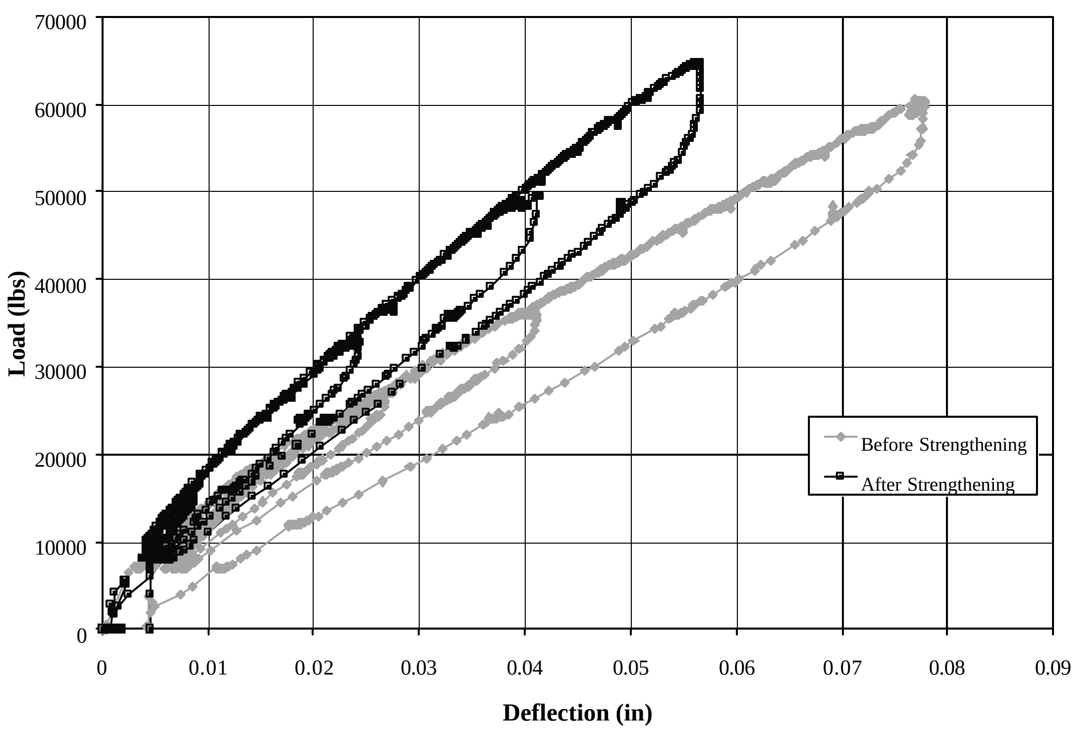

Figure B.13: Load versus deflection of joist mid-span before and after strengthening [Load Test A-1 and B-1] (1 in. = 25.4 mm, 1 lbs. = 4.45 N)

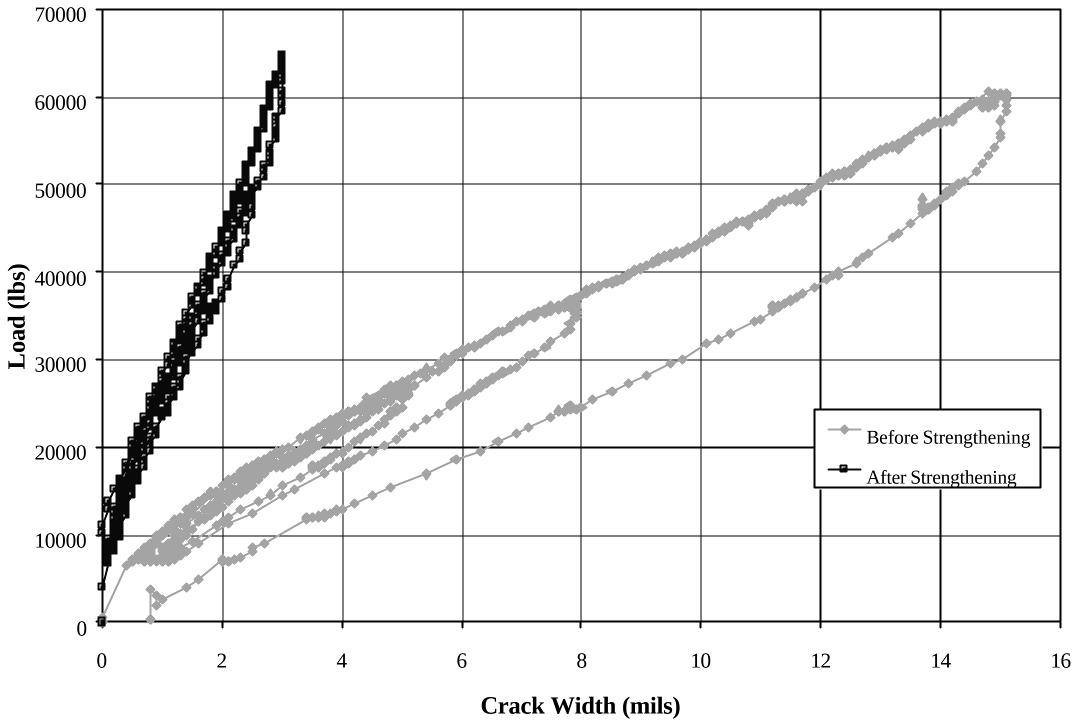

Figure B.14: Load versus crack width at joist mid-span before and after strengthening [Load Test A-1 and B-1] (1 mils = 0.001 in. = 0.0254 mm, 1 lbs. = 4.45 N)

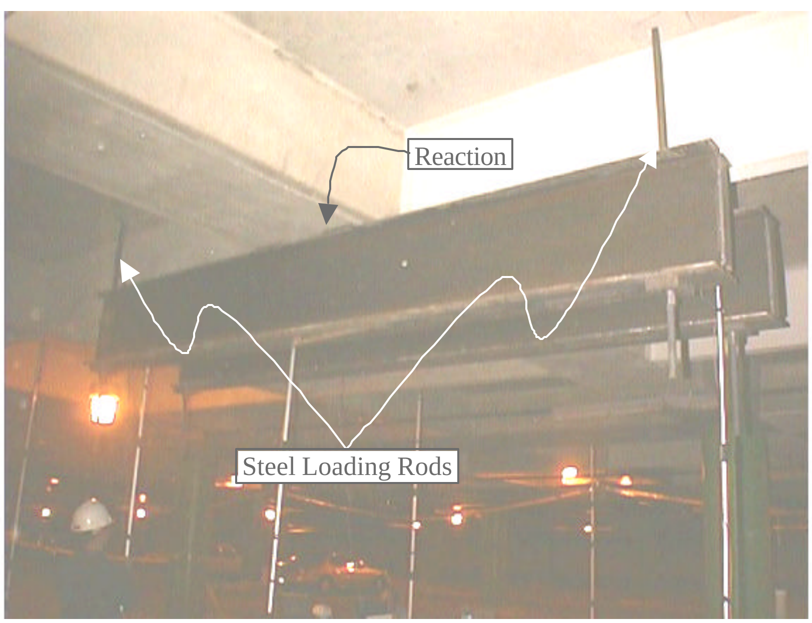

Figure B.15: Loading apparatus used for Load Configuration 2

Case Study #11: Pittsburgh, Pennsylvania: Closed Loop

The presence of shear cracks near the dap ends of 1,400 prestressed concrete beams in a parking garage led to their repair using externally bonded CFRP sheets as reinforcement (Sawyer, 1998 and Wuerthele, 1999). Load tests were performed on 20 representative beams in order to verify the strengthening was effective (Mettemeyer, et al., 1999 and Gold, et al., 2000). Each test was performed using the closed loop method on two isolated, simply supported double tee beams simultaneously as shown in Figure B.16 and Figure B.17. Figure B.16 shows the view of the closed loop testing method from below the test members. The reaction beam and the inverted tee, against which the reaction beam reacts, as described in Section 2.2.2, are both shown in this figure. Also shown are the LVDTs mounted on aluminum tripods, which are used to record the deflection of the two test members during the load test. The data acquisition unit, which records the values of load and deflection during the load test, is also shown in Figure B.16. Figure B.17 shows the view of the closed loop test method from above the test members. In this figure, the two test specimens, which have been isolated from the rest of the slab, are shown. The transport box, which contains the electric pump used to supply the fluid to the hydraulic jacks, is also shown. The hydraulic jacks apply the test loads to the spreader beams, which concentrate the loads on the two stems of each double tee, as described in Section 2.2.2. All the tests were completed in less than ten days, and the interruption to the flow of traffic was minimal, due to the method of testing and the efficiency with which the tests were conducted. The effectiveness of the CFRP strengthening system and the ability of the beams to carry their design loads were successfully demonstrated by the rapid load testing.

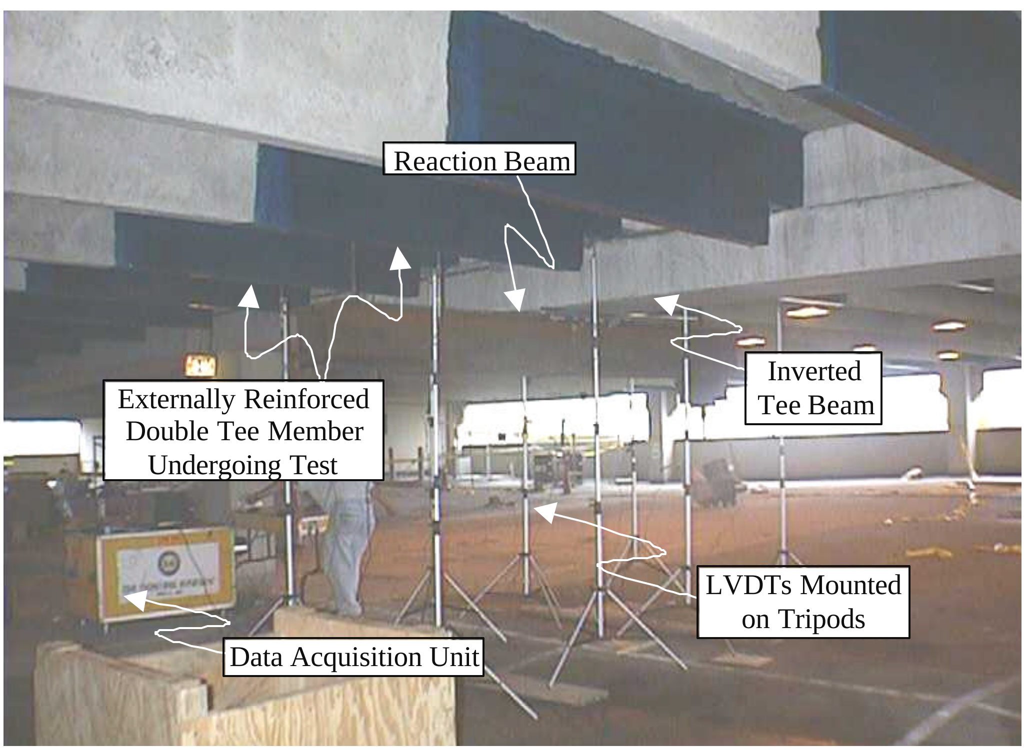

Figure B.16: Closed loop method from below the test members

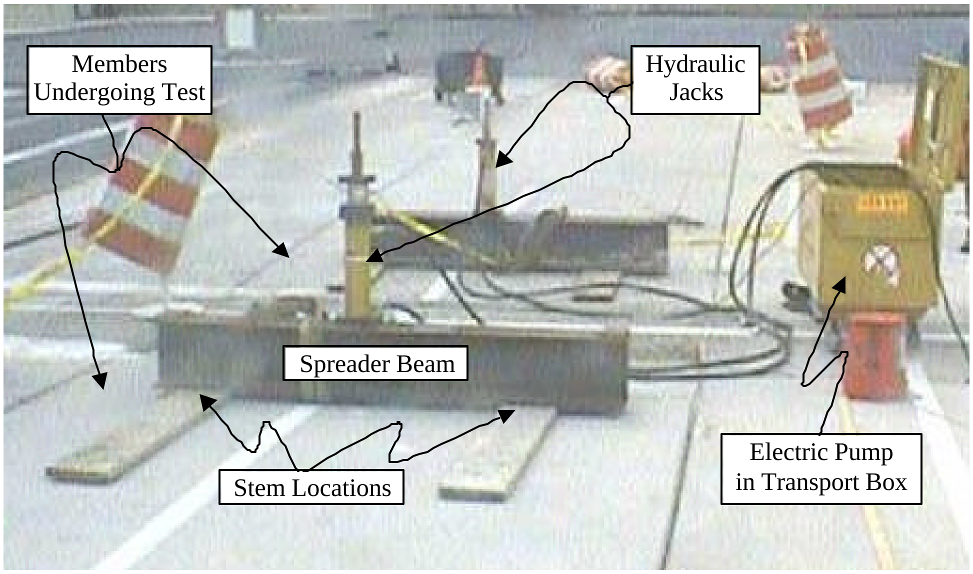

Figure B.17: Closed loop method from above the test members

Case Study #12: Los Angeles, California: Vehicle

The following case study discusses the strengthening of the structural deck at a power plant (Bick, 1998). The deck is a post-tensioned, one-way, concrete slab that is 11 in. (279 mm) thick. The slab is edge supported by steel wide flange sections, and the construction is non-composite. Strengthening was required as a result of a loss of post-tensioning tendons due to corrosion. The strengthening system utilized externally bonded CFRP sheets. The sheets were installed at intervals along the slab's soffit for positive moment strengthening and at intervals along the top of the slab for negative moment strengthening (Figure B.18).

Load tests were conducted in order to confirm the addition of positive moment strength provided by the CFRP sheets installed on the slab's soffit. The evaluation consisted of an in situ load test of a typical slab before and after the CFRP soffit reinforcement was installed (the CFRP reinforcement on the top of the slab was in place for both series of tests). Load was applied by positioning a forklift at various locations along the span of the slab and carrying varying amounts of additional load, as described in Section 2.2.2. A preliminary analysis of the slab was used to gage the loads and positions needed to induce given moments in the slab. Slab deflection measurements were taken at several locations to determine the actual moments induced in the slab at the time of testing. Strain measurements in the concrete and the CFRP sheets were then used to determine the stresses in these materials. These values were compared with expected stress levels determined by analysis to ensure that the CFRP was providing additional strength to the member.

The baseline load test was executed before installation of the positive moment CFRP reinforcement. The purpose of this test was to provide a basis for evaluating the structure after it had been strengthened. The addition of strength to the system provided by the CFRP was confirmed by a comparison to the system before strengthening. Relatively low levels of load were applied in this test so as to prevent permanent damage to the structure. Two levels of load are used for the baseline test. The forklift is initially unloaded; therefore the applied load was only the dead weight of the forklift (Test Cycle 1). The total load on the front axle of the forklift was 5,150 lbs. (22.91 kN) at this level. The forklift was positioned at five different locations on the slab, with each location causing a larger moment at the center of the slab. Each position was maintained for a minimum of two minutes so that deflections could stabilize. Moments were then decreased by moving the forklift back to the same positions in reverse order. These positions were again maintained for two minutes each. This initial test was primarily used to calibrate and check the instrumentation. For the second load cycle, a surcharge of 300 lbs. (1.33 kN) was carried by the forklift (Test Cycle 2). This results in a total front axle load of 5,645 lbs. (25.11 kN). The position of the forklift was varied in a similar fashion to Test Cycle 1. Readings from all devices were recorded at five-second intervals throughout the duration of the cycle.

The after-strengthening load test was performed after the installation of CFRP sheets on the soffit of the tested slab. The CFRP sheets were installed and allowed to cure. Higher levels of load were applied in this test. The purpose of this test was to confirm the addition of strength to the system at load levels corresponding to service load levels and above. The after-strengthening load test consisted of three load cycles. Load Cycle 3 was identical to Load Cycle 2 (baseline test) for a direct comparison. The load levels were then significantly increased. Load Cycle 4 was performed using the forklift loaded with a surcharge of 1,800 lbs. (8.01 kN), resulting in a front axle load of 10,900 lbs. (48.5 kN). The final cycle, Load Cycle 5 (Figure B.19), was then run with a surcharge of 3,600 lbs. (16.01 kN), resulting in a front axle load of 16,660 lbs. (74.11 kN). The incremental positions of the load remain the same as the positions in the baseline test. Stabilization of all deflection readings at each increment was verified to ensure the safety of the test. Readings from all instruments were recorded at five-second intervals throughout the duration of each load cycle.

The system's performance was evaluated based on its response to the bending moments induced by the test loads. The overall performance of the entire system was evaluated as well as the performance of the CFRP considered separately. The evaluation of the overall structural integrity of the system is based on an analysis of the linearity of the structure's response to loading. The linearity of the structure's response was evident in the relationship of the load versus the deflection of the system. The load levels induced during testing were all within the structure's elastic capacity. This was verified by investigating the load-deflection relationship for the load cycles in the after-strengthening test.

Figure B.18: Top of deck after strengthening

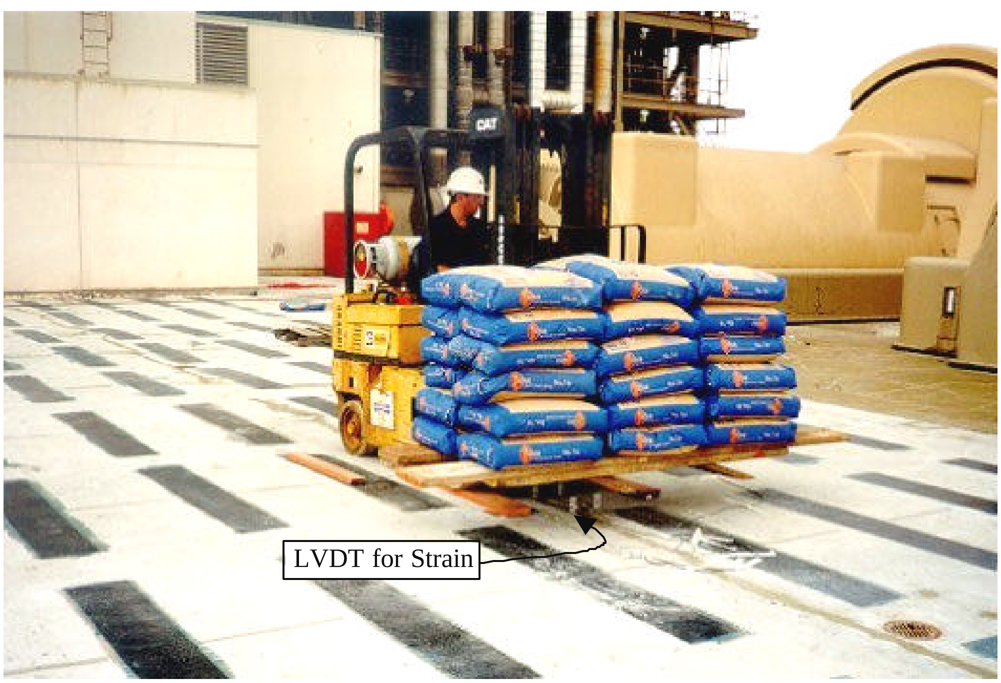

Figure B.19: Forklift loaded with 36-100 lbs. (0.44 kN) sandbags

Case Study #13: Norfolk, Virginia: Vehicle

The concrete slab of a marine pier was load tested in order to assess its structural performance after it was strengthened with externally bonded FRP reinforcement. The load test involved measuring the deformation of the slab under the load of a large forklift operating on the deck. The forklift was loaded to simulate the effects of carrying coils that are stored in this facility. The results of the test indicate that the structure can service the needs of the facility with an adequate factor of safety. The only concern is for the non-structural, asphalt topping which may not be sufficient to sustain the anticipated loads.

The purpose of the load test was to simulate the effect of design load conditions. For the case of the current study, the governing design load results from a large forklift operating on the top of the slab. The flexural performance of the slab at mid-span was of primary interest. One typical structural bay was tested after strengthening with externally bonded FRP sheets. Load was applied by positioning the in-service forklift on top of the slab (Figure B.20), as described in Section 2.2.2. The load was increased incrementally by varying the position of the forklift and the amount of additional weight the lift carried. Measurements were recorded as the forklift was positioned at five locations along the centerline of the bay. For each of these positions the forklift carried additional loads.

The testing equipment used consisted of LVDTs for measuring deflections and electrical resistance strain gauges and extensometers for measuring strains. The LVDTs were mounted on aluminum tripods, which sat on temporary scaffolding below the test member, as shown in Figure B.21. Deflection measurements were taken at evenly spaced intervals along a line located mid-way between the column lines. These measurements were used to plot the deflected shape of the slab along this line. By differentiating the deflected shape twice, the curvature of the slab along the same line was determined. Assuming a constant flexural stiffness, the distribution of moments in the slab is directly proportional to the curvature. This differentiation was performed numerically by finding the slope between deflection data points. The maximum curvature of 135×10^{-6} in.$^{-1}$ was measured in the slab at mid-span. The level of induced curvature suggested that the slab was behaving well compared to its limit states. Under the applied load the slab was at 40% of the yielding point of the steel and at 37% of its ultimate capacity (safety factor of 2.70). This suggests that the slab is well within serviceability limits under the applied load, and the slab has adequate reserve to resist overload conditions.

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Figure B.20: Loaded forklift positioned over center of tested bay

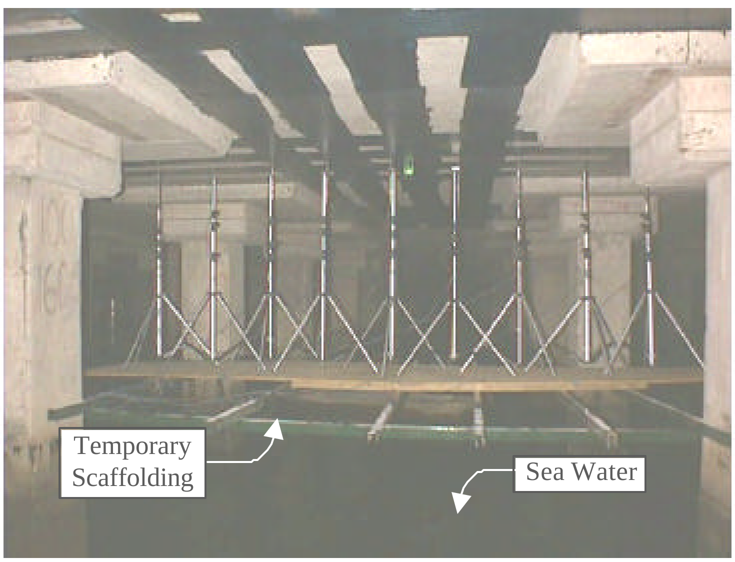

Figure B.21: LVDTs mounted on tripods sitting on temporary scaffolding below pier

Case Study #14: Pine Bluff, Arkansas: Dropped Weight

This load test was conducted as part of a pilot project. The project involved strengthening and testing of one beam for shear. The beam under consideration was representative of about 54 beams in similar condition. These beams were damaged due to overloading and impact loading. A large number of shear and flexural cracks were observed on most of the beams indicating a significant degradation in stiffness. A rapid load test evaluation was conducted before and after strengthening. Each load test consisted of both static and dynamic loading. Static loading was achieved via a forklift carrying a payload weighing about 14,000 lbs. (62.3 kN). The forklift was slowly driven on top of the beam toward mid span and then back. Dynamic loading was induced by using a forklift to drop the payload onto the beam from different heights. LVDTs were used to measure the displacement of the beam at mid span and close to the end supports, as shown in Figure B.22. Accelerometers were used to measure the acceleration of the beam under the dynamic loads. The results of the static and dynamic tests indicate that the strengthening resulted in an increased stiffness of the member.

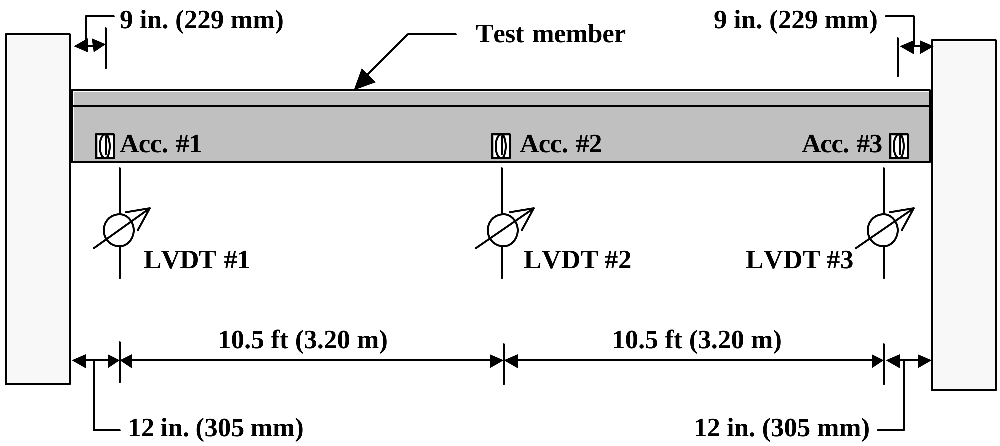

Figure B.22: Schematic drawing shows location of LVDTs and accelerometers