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In-situ Load Testing to Evaluate New Repair Techniques

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Abstract

The lack of accepted design and construction specifications for new structural repair technologies may warrant on-site evaluations of these systems. Rapid in-situ load testing offers an effective way of assessing the performance of a strengthening system installed on an existing structure. This type of load test is unique in that it features concentrated loads of varying magnitude, cyclically applied over a short time period. The paper reports on a prototype system used by the University of Missouri at Rolla to evaluate flexural strengthening systems using bonded composite materials. The development of this system aims to provide a powerful tool in the assessment of new techniques and materials used in structural repair.

Introduction

Growing interest in the rehabilitation of existing buildings and infrastructure has spawned a need for innovative methods of structural strengthening. To this end, significant investigations into the use of such technologies as bonded carbon fiber reinforced polymer (CFRP) sheets to strengthen concrete structures have been conducted [1, 2]. However, design specifications and construction standards have not yet been developed for many of these new technologies. Due to this lack of recognized guidelines, there is reluctance among building professionals to implement such systems. In order to allow the building professional to use new technologies with confidence, an on-site performance assessment may be warranted.

This paper reports on in-situ load testing procedures that have been used by the University of Missouri at Rolla (UMR) to evaluate CFRP sheet bonding systems that are used to increase the flexural capacity of concrete beams and slabs. The paper gives specific reference to two-way flat plates or slabs; however, the methods described are easily extended to other CFRP strengthened concrete floor systems. UMR is currently working to extend the capabilities of this practice by developing general guidelines for evaluating new repair technologies.

Testing Objectives

Rapid in-situ load testing has been used in other countries to confirm structural performance compliance. This technology has been successfully adopted to evaluate strengthening systems involving the use of externally bonded CFRP [3, 4]. The purpose of the load test is to verify that the CFRP strengthening system will perform as intended. It should be emphasized that the test does not seek to provide a condition assessment of the existing structure. The testing procedures described herein presume that the condition of the existing structure has been competently evaluated and that the purpose of the strengthening system is well defined.

The load test is designed to simulate the effect of design service load conditions on the in-situ structure with hydraulic jacks which are relatively easy to install and control (see Figure 1). Since the purpose of the CFRP strengthening system is to increase the flexural capacity, the loads are intended to induce the same critical bending moments in the structure as the design loads would produce. By directly applying the load on the actual in-situ structure, measurements may be used to evaluate the performance of the system. Furthermore, this type of load test offers immeasurable psychological benefits especially to clients and owners.

As a common example, the case of a two-way slab system strengthened for flexure is discussed in this paper. In the case of a slab, the design service load is typically a uniform downward (gravity) pressure acting over the entire surface of the slab. Since the load from the hydraulics is significantly more concentrated, it is only possible to simulate the effects of the design service load on small portion of the slab. The test, therefore, focuses on evaluating the slab on a unit width basis. Testing a small portion of the slab has the additional benefit of maintaining a higher degree of safety during testing. If any serious damage to the slab were to be done, this damage would be localized. The results of localized damage would be less likely to result in any catastrophic failure of the entire system.

Description of the Load Test

Testing Equipment

Based on the recommendations and experience of load test specialists operating in Europe, UMR has developed a prototype portable load test system. The system is contained in two boxes and is easily shipped to a site. Typical installation and setup of the equipment on-site can be completed in about 4 to 5 hours.

Figure 1 shows the loading apparatus. It consists of hydraulic jacks with pedestals, rigid extensions, and hoses, and a hydraulic pump contained inside the metal box. The electrically operated pump need not be removed from the box and is remotely controlled.

Figure 2 shows the front panel of the data acquisition box during field use. The top portion of the panel includes the control unit for signal processing/recording, a four-pen strip-chart recorder, and two display monitors. The bottom portion of the panel features cable connectors for pressure transducers, LVDT's, and strain gages.

Testing Configuration

The hydraulic jacks used to supply the test load must be provided with an adequate reaction. In a push-type test, as shown in Figure 1, the jacks react against the floor above using its dead load as counterweight. A pull-type test may be required in some situations where there is no surface to react against above the tested slab. In this test, the jacks pull against steel rods or chains from underneath the tested slab. A suitable reaction for the steel rods or chains must be provided.

In order to evaluate the slab on a unit width basis, it is necessary to provide a region of constant moment in the direction perpendicular to the primary span. This may be accomplished by providing two concentrated loads spaced a few feet apart along the perpendicular direction (see Figure 3). In this way, variation of the moment over the unit width may be minimized.

Furthermore, since the tested unit width is not isolated from the adjacent portions of the slab, it is necessary to increase the load magnitude to compensate for the additional stiffness provided by the adjacent portions. This stiffness contribution, known as load sharing, must be accounted for in the analysis of the system. This is most easily achieved by using a two-dimensional finite element analytical model. More details of modeling are given in the “Analytical Modeling” section.

Slab deflection measurements are taken at several locations using LVDT’s (see Figure 4). The strain distribution throughout the depth of the slab is measured with LVDT’s and strain gages mounted on the top and bottom of the slab at the location of the critical section. The deflection measuring LVDT’s may be mounted on stands resting on a stable floor (see Figure 5) or hung from the floor above.

Testing Procedure

The test loads are applied in quasi-static load cycles. Several initial cycles at low load levels are run to insure that the instrumentation and data acquisition system are functioning properly. The actual testing cycles are then started. Each cycle starts at zero load and involves at least four approximately equal load steps up to the maximum load level followed by at least two steps back to zero load. The load steps allow for monitoring the safety of the test; if deflection measurements do not stabilize at any load step, the test is halted. Deflection and strain measurements are recorded continuously during testing; Figure 6 shows a sample deflection history for two load cycles.

Evaluation

The evaluation of the system uses a combination of analytical modeling and test results. The analysis is used to theoretically predict the behavior of the CFRP system, and the evaluation is based on establishing agreement between the measured response and the theoretical behavior.

The first load cycles are maintained within the linearly elastic range of the structure and are used to verify that the CFRP is engaged. Measured strain values are used to determine the strain distribution through the depth of the slab. Based on material properties, this strain distribution may be converted to an internal moment (see Figure 7). This internal moment is then correlated with the moment determined through use of the analytical model for the given test load. If there is agreement between the two values, it may be concluded that the CFRP is engaged. It is typically possible to show that for the

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measured strain distribution, the section without CFRP is not capable of resisting the applied moment.

It is necessary that this portion of the evaluation be performed in the linearly elastic range of the slab. If the slab becomes non-linear, it would be necessary to determine the initial strain conditions. The initial strain conditions are mainly a result of dead load moment and strains induced by prestressing (if present). These strains are difficult to assess with the required accuracy. Therefore, the structure is kept within the elastic range so that these effects may be neglected according to superposition.

The linearity of the structure is verified by plotting the measured load versus deflection data. Figure 8 shows sample load deflection data from a structure loaded in the linearly elastic range. The magnitude of the strains are not used to gauge the linearity of the structure, since the measured strains result from test loads only. The initial strains are not included and would need to be added for such an evaluation.

The second part of the evaluation involves applying loads above the elastic range nearer to the ultimate capacity of the slab. Ideally, this load level simulates 85% of the factored load condition. Again, since the test is only loading a small region, there is little chance of doing any permanent damage to the structure. However, this load level will insure that the CFRP sheet will remain bonded at loads near ultimate. After a series of cycles at this higher load level, the structure is again loaded with cycles in the elastic range. An evaluation of the strain distribution is again performed to insure the CFRP is still engaged, and the repeatability of the strain measurements is checked.

Analytical Modeling

For a meaningful evaluation, it is necessary to analytically determine the magnitude of moments induced by the test loads. This requires an analytical model that accurately represents the in-situ situation. A preliminary two-dimensional finite element model is developed that represents the geometry of the tested span (See Figure 9). Some initial assumptions are made regarding the boundary conditions and material properties. It has been found that, in most situations, a linear model is sufficient. The preliminary model is used to design the load test. Once the load test has been performed, the model is refined based on test results.

There are two parameters of the analytical model which must be refined based on the load test results. The first is the fixity of the support conditions. This refinement is made by matching the measured shape of the elastic curve to the shape from analysis. The calculation procedure involves calculating the ratio of measured quarter-span deflection (δ_B and δ_D) to mid-span deflection (δ_C). The deflection values used are taken in reference to a point near the support (δ_A and δ_E) to eliminate any support displacements. The equation for calculating this ratio is given in Equation (1).

$$R = \frac{\frac{1}{2}(\delta_B + \delta_D) - \frac{1}{2}(\delta_A + \delta_E)}{\delta_C - \frac{1}{2}(\delta_A + \delta_E)} \tag{1}$$

The value of R resulting from this calculation is averaged for all measurements taken at the load levels within the elastic range of the materials. The boundary conditions on the edges perpendicular to the primary span are then adjusted in the model until the value of R calculated from analytical results corresponds to the experimental R value. The highest values of R corresponds to a span with pinned ends (no rotational stiffness) and the lowest R values indicate a fully fixed support condition. The boundary conditions on the edges parallel to the primary span may be adjusted similarly using the deflections measured in the transverse direction for Equation (1).

The second refinement is an adjustment of the modulus of elasticity for the concrete. This refinement is not necessary for evaluating bending moment magnitudes and distributions, but it is required to correlate deflection data to the analytical model. This adjustment is rather straight forward. The assumed modulus of elasticity ($E_{preliminary}$) is simply multiplied by the ratio of a deflection value determined from analysis with the assumed modulus ($\delta_{preliminary}$) to the corresponding measured deflection ($\delta_{measured}$). The value of mid-span deflection referenced to a point near the support will again be used for this calculation. The equation for calculating the refined modulus is given in Equation (2).

$$E_{refined} = \frac{(\delta_C - \delta_A)_{preliminary}}{(\delta_C - \delta_A)_{measured}} E_{preliminary} \tag{2}$$

The resulting of refined modulus of elasticity should be within reason for the in-situ concrete. Where possible, separate material coupon tests are conducted to verify the concrete material properties.

With the refinements made, the agreement between all measured deflections and deflections resulting from analysis are confirmed. Figure 10 shows sample elastic curves plotted from analysis and test data. The new refined model is then used to accurately determine the magnitudes and variations of bending moments in the slab. The moment induced at the critical section by the test loads may also be matched by a multiple of service loads. In this way, the level of load that the test load simulates is determined.

Conclusion

The lack of accepted design guidelines for the use of externally bonded FRP reinforcement will soon be overcome. In the interim, the practice of specific and well-designed in-situ load tests can be a powerful tool for the assessment of the rehabilitation work. Future use of load testing to investigate the durability of CFRP materials and to evaluate other new technologies is expected.

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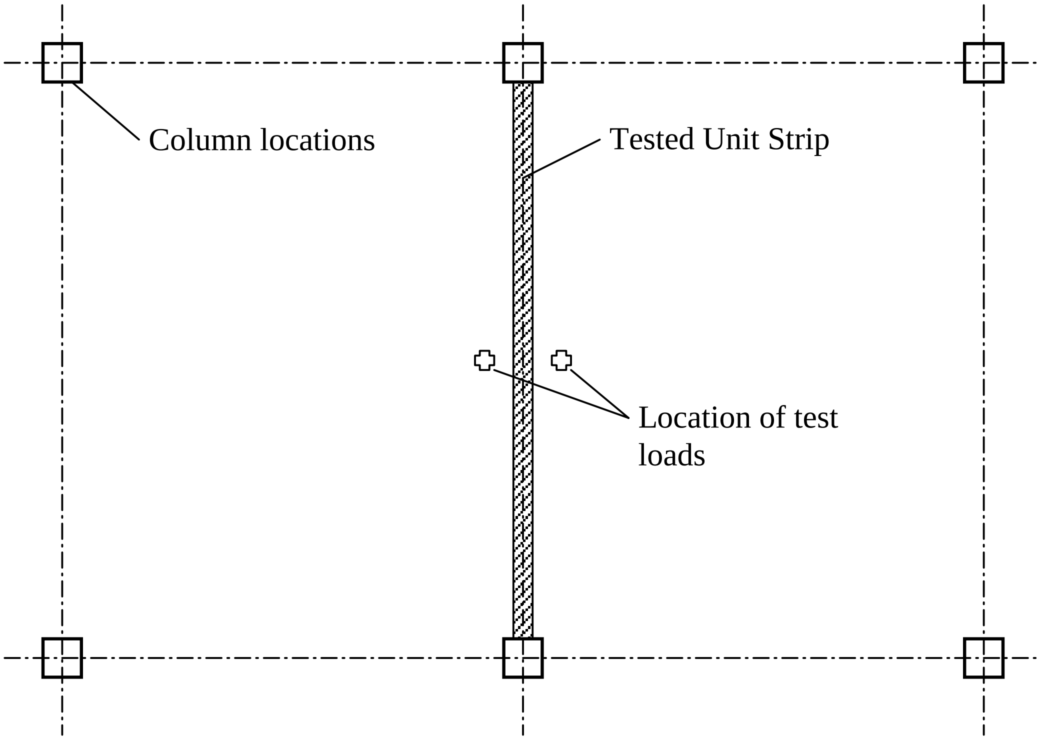

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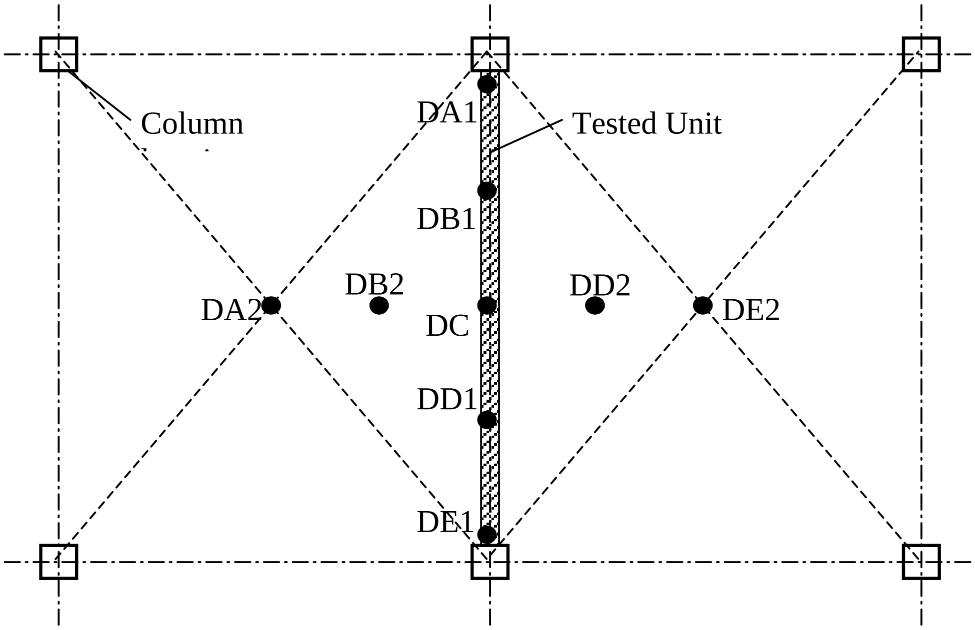

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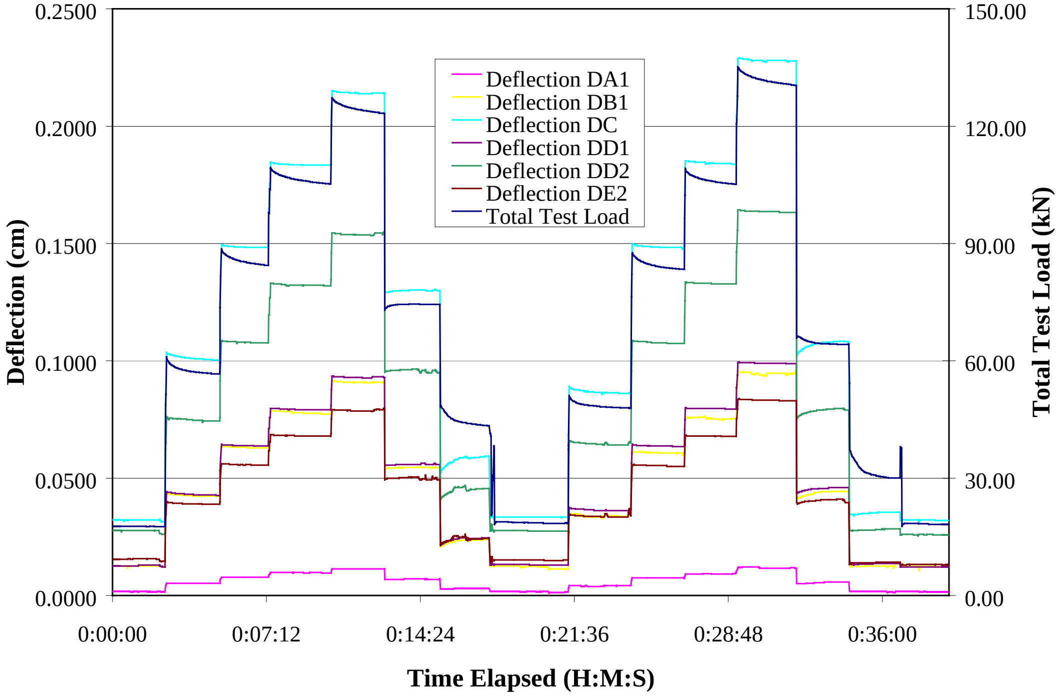
Figure 5: Photograph of instruments to measure deflections used by UMR



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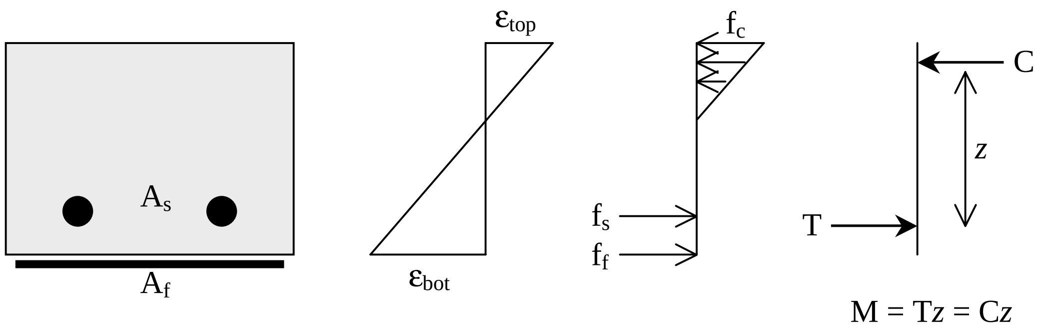

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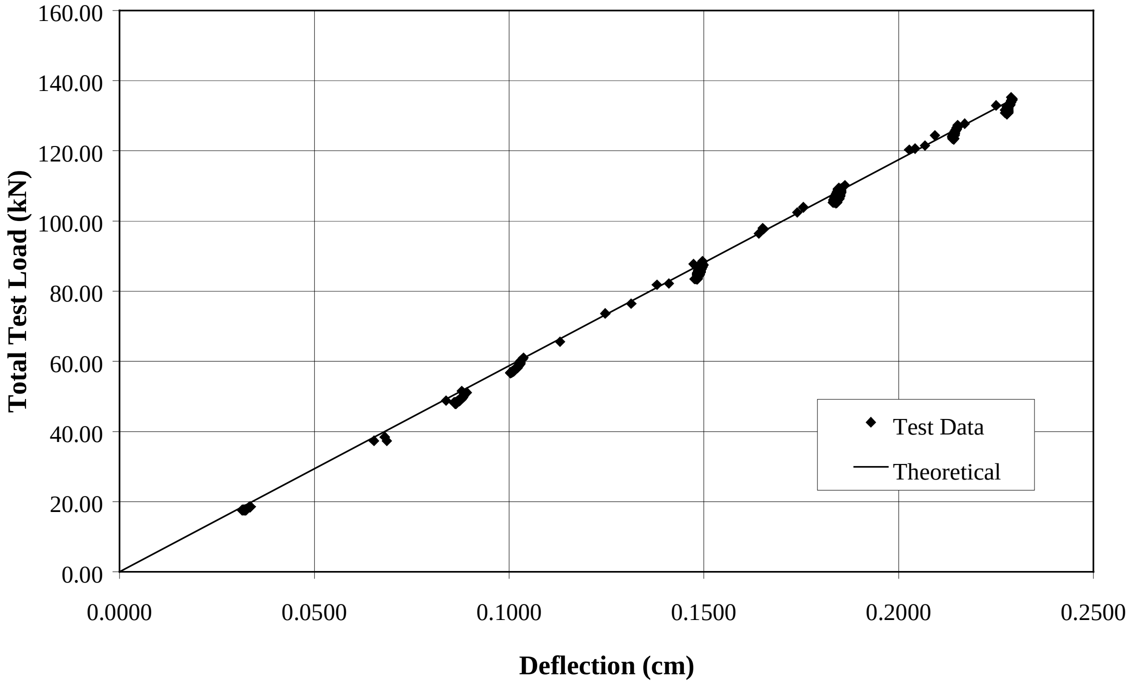

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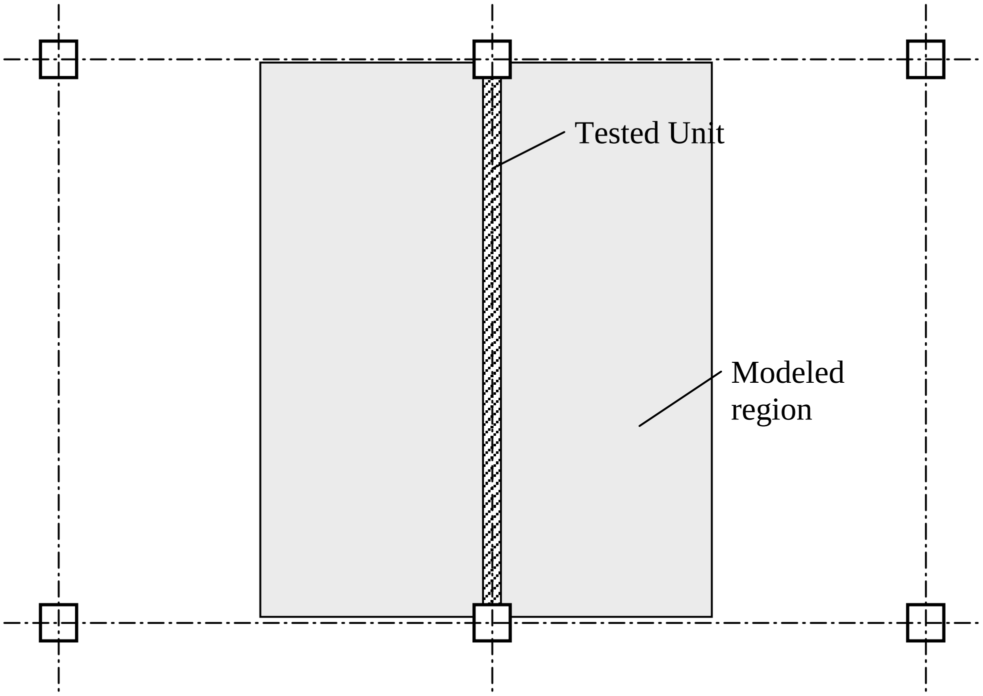

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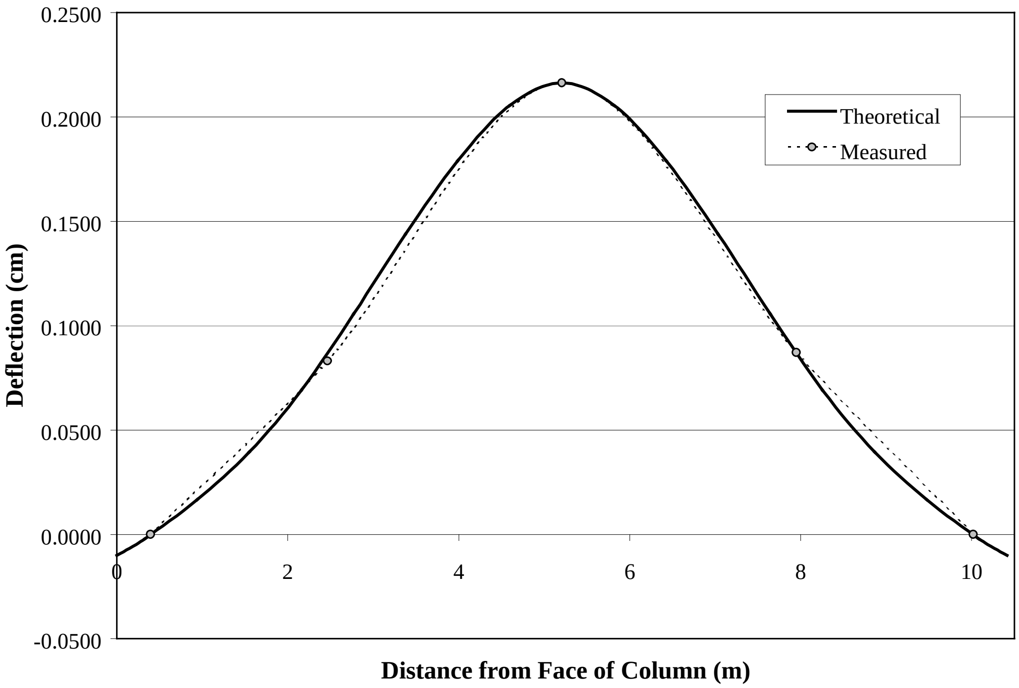

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