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(i) **Full Title**: Monotonic and Cyclic Behaviour of Helical Pile Connectors in the Vertical Direction

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ABSTRACT

The helical pile is a foundation system that is used to support new residential and commercial buildings, and for stabilizing repairs of existing structures. The helical pile represents an attractive option to upgrade the seismic resistance of foundations. This necessitates a good understanding of the seismic performance of the specialized connectors linking the pile shaft to the concrete foundation. An experimental program is initiated at the University of Western Ontario to investigate the seismic performance of these connectors; to develop models that can be used in finite element analysis to describe their behaviour; and to propose modifications to enhance their seismic performance, if necessary. In this program, eight specimens were tested to assess the behaviour of two types of these connectors under different loading modes. It was concluded that connectors with an uplift bracket are required for seismic applications to control uplift displacement due to foundations rocking.

KEYWORDS: Helical Pile, Connector, Experimental, Model, Monotonic, Cyclic, Foundation, Stiffness, Strength.

INTRODUCTION

Foundations are the structural elements that transmit the load of the structure to the underlying soil strata. Normally, foundations would fulfill the intended purpose if properly designed and constructed, with due consideration of soil conditions and different loading events. Improper soil investigation and/or inadequate consideration of seismic activity are among the factors that necessitate the evaluation of the performance of the foundation and then suggesting a repair or rehabilitation. Other factors may include heave or shrinkage due to activity of expansive or soil slope movement.

Screw or helical piles have been used in practice for almost a century, but they have been utilized as a repair or a retrofitting tool for geotechnical and foundation applications only in the last fifteen years. They are considered a very efficient retrofit technique for moderately loaded buildings (Carville and Walton, 1995). A typical helical pile is shown in Figure 1 and it consists of a steel shaft and a number of helical plates welded to it. Various sizes of helices and shaft cross sections are available in the market. Depending on the required capacity and the soil properties, the number and dimensions of the helical plates as well as the diameter of the steel shaft can be calculated (Bobbitt and Clemence, 1987; Rao and Parsad, 1991).

Hoyt et al. (1995) assessed the buckling strength of helical piles using numerical modeling. It was found that buckling is a practical concern only in the softest soils. Rao et al. (1989) and Bobbitt and Clemence (1987) found that helical piles are very effective in resisting uplift forces. They also made recommendations for the size and spacing of the helical plates to resist specific uplift forces. An experimental study conducted by Parsad and Rao (1996) evaluated the lateral capacity of helical piles and proved that the existence of helical plates increases the lateral capacity by 20% to 50% over that of the shaft.

Helical piles are attached to existing foundations using a specialized connector. All available studies have been concerned with the performance and capacity of the helical pile itself. To the best of the authors' knowledge, there are no studies that have been conducted to assess the capacity and performance of the specialized connectors attaching the helical piles to the concrete foundations. The characteristics of the connector may govern the effectiveness of the helical pile and its performance as a retrofitting tool. The current study is part from a comprehensive research project conducted at University of Western Ontario to evaluate the performance of all components of the helical foundation systems. The main objectives of the presented study are:

1. Evaluate the strength, elastic stiffness and performance characteristics of helical pile connectors in the vertical direction.
2. Establish a suitable model that can be used to predict the combined behaviour of foundation/helical pile systems.
3. Propose and evaluate new modifications to the connectors design to rectify any deficiencies in its performance revealed during the evaluation process of the original design.

In this paper, the performance characteristics of these specialized connectors when subjected to loads in the vertical direction are defined experimentally. These characteristics include: capacity, stiffness and cyclic behaviour. The experimental results are then utilized to formulate a simplified model that can be used to predict the performance of these connectors when subjected to a vertical downward load (pile in compression) or a vertical upward load (pile in tension). The paper also describes a possible modification to the connector design and its effect on the performance characteristics.

Foundation Specimens

Four plain concrete (PC) and four reinforced concrete (RC) foundation specimens were constructed and tested as part of this study. The dimensions of these specimens were 1.00x0.60x0.20 m. The thickness was chosen to be 0.2 m to match the common thickness in houses foundations. The size of these specimens was chosen such that local effects created by the test setup would not affect the results. This was confirmed by conducting a finite element analysis of the tested specimens.

PC and RC specimens were cast using the mixes shown in Table 3.1. A mechanical vibrator was used during pouring the concrete to ensure a homogenous section that is free from voids and honeycombing. The specimens' surface was covered after casting using a polyethylene sheet for forty-eight hours after which the formwork was dismantled and the specimens then covered by wet burlap for four days.

The average compressive strength of the PC specimens at the time of testing was 35 MPa and that of the RC specimens was 38 MPa. The top and bottom reinforcement of the RC specimens were three M20 bars in the long direction, and eight M10 bars in the short direction. A photograph showing the reinforcement is given in Figure 2.

Helical Pile Specialized Connectors

The connectors tested in this study were manufactured by Hubbell Power Systems Inc, Centralia, Missouri and were composed of either two-pieces (Vertical Bracket, and T-Pipe) or three-pieces (Vertical Bracket, Uplift Bracket, and T-Pipe). A photo showing the three-piece connector is given in Figure 3. To install the helical pile connector, two-wedge bolts size ½" (12.7 mm) diameter x 4¼" (108.0 mm) length would connect the vertical bracket to the concrete foundation;

and five-wedge bolts size 5/8" (15.9 mm) diameter x 7½" (190.5 mm) length would connect the uplift bracket to the concrete foundation. Figure 4 shows a photo of a typical wedge bolt.

The two-piece connector is expected to resist only compressive forces in the piles. Such forces are transferred to the pile through bearing of the concrete foundation on the vertical bracket. For seismic areas, the three-piece connector is expected to allow transferring tensile forces from the foundation to the piles through the wedge bolts connecting the uplift bracket to the concrete foundation.

Installation of Connectors

The main steps involved in installing the connectors can be summarized as follows:

1. The concrete specimens were slightly chipped at their edge in order to ensure that the bracket is fitting flush against the edges of the concrete. Ensuring such position of the vertical bracket minimizes the eccentricity of the load on the helical piles. The effect of such eccentricity on the pile capacity was explained by Hoyt et al. (1995). They concluded that buckling of the shaft would be possible if eccentricity existed.
2. The vertical and/or the uplift brackets were placed on the surface of the concrete and used as templates for drilling two or seven holes.
3. The wedge bolts were driven into the concrete by hammering and then the nuts were tightened to the torques specified by the bolts manufacturer, which were 55 lb.ft. (74.6 N.m.) for the ½" (12.7 mm) bolts and 90 lb.ft. (122.0 N.m.) for the 5/8" (15.9 mm) bolts. It should be noted that the bolts connecting the vertical bracket to the concrete specimen were not installed at the same position in all specimens. This was done to simulate the actual

field condition where the vertical and the horizontal clearance around these bolts will lead to similar conditions.

Test Setup

In this section, the test setup is explained. This includes its different elements and the flow of forces in the tested specimens compared to field conditions. Figure 5 shows a schematic of the different elements of the setup and Figure 6 shows a photograph of the setup. The test setup was designed to simulate the load transfer mechanism occurring when the helical piles are subjected to vertical tensile or compressive loading and is characterized by the following:

1. The uplift movement of the concrete specimen was prevented by two clamping beams held to the rigid floor using four steel rods.
2. The downward movement of the blocks was prevented directly by the rigid floor.
3. The horizontal movement of the block was prevented by using two steel angles fixed to the floor.
4. Eight LVDTs were used to measure the concrete block vertical and lateral movement, the vertical bracket vertical and lateral movement, and the uplift bracket vertical and lateral movement.

The load was transferred from the MTS loading machine to the specimen through a specially designed loading shaft. The threaded end of this shaft was connected directly to the MTS machine. The diameter of the other end (53 mm) was 2 mm less than the inner diameter of the T-Pipe. This allowed sliding the shaft inside the T-Pipe and connecting them using four 22 mm pins.

A downward loading from the MTS machine simulated a compressive force being transferred from the foundation to the helical pile. As can be seen in Figure 6, such a force is mainly transferred through bearing of the vertical bracket on the concrete specimen. An upward loading from the MTS machine simulated the transfer of a tensile loading from the foundation to the pile. In this case, the force will be transferred to the foundation through the wedge bolts connecting the vertical and/or the uplift bracket to the concrete foundation.

Loading

The loading was provided by a 1500 kN hydraulic Jack with a maximum stroke of 160 mm. A load cell with maximum capacity of 245 kN was used to record the actuator readings. Two types of tests were conducted:

1. Monotonic Loading Tests:

   A displacement control approach was used where the displacement was incrementally increased with a rate of 1 mm /minute. These tests were conducted to define the static behaviour of the specialized connectors.

2. Cyclic Loading Tests:

   A displacement-controlled approach was used to apply several cycles of loads. In each cycle, the actuator was first pushed to a displacement d_1 in the positive direction then pulled to a displacement d_2 in the negative direction. The values of d_1 and d_2 are incrementally increased in the following cycles. It should be noted that this type of loading is static in nature and does not capture the effect of high loading rates that are expected during earthquakes. Such high loading rates are expected to result in a higher capacity and thus the results of the conducted tests are considered to represent conservative evaluation of the connectors' seismic behaviour (Ghobarah et al., 2004).

Monotonic Behaviour of PC Specimens

As discussed before, a compressive force in the pile will be transferred through bearing of the concrete foundation on the vertical bracket. Preliminary calculations were conducted based on the available helical pile capacities and it was concluded that the bracket and the concrete would not fail during such a transfer. This led to a conclusion that monotonic tests are not required to describe such a transfer. On the other side, the behaviour of the connector during transferring a tensile force from the foundation to the helical pile was expected to be highly dependable on its configuration and thus two monotonic tests were conducted.

In the first test (V1), a two-piece connector was used to enable designers and researchers to assess the behaviour of buildings fitted with such brackets. The test also allowed evaluating the improvement in the tensile capacity associated with using a three-piece connector. In this test, the load was first transferred from the T-Pipe to the vertical bracket through bearing of its flange on the vertical bracket stiffeners as shown in Figure 7. This resulted in displacing the vertical bracket until the clearances around the wedge bolts, connecting it to the concrete specimen, were eliminated.

In the case of test V2, where a three-piece connector was used, the load was transferred from the T-pipe to the connector by bearing of its flange on the uplift bracket horizontal leg, as shown in Figure 8. The five wedge bolts connecting the uplift bracket to the concrete foundation had almost zero clearances around them and thus the uplift bracket started directly to resist the applied loads. The vertical bracket was not having any share in resisting these loads.

Figure 9 shows the load-deformation curve for both specimens. The horizontal axis represents the vertical deformation of the connector and the vertical axis represents the load applied by the MTS machine. The vertical deformation of the connector was corrected by accounting for Concrete Block rotation. The initial stiffness of the three-piece connector was much higher than that of the two-piece connector.

During test V1, minor cracking in the concrete surrounding the wedge bolts was observed at displacement of 7.5 mm (Point A on the curve). A photo showing these cracks is given in Figure 10. The specimen ultimate load was 51 kN. This load was associated with shear failure of one of the wedge bolts (point B). The second bolt was able to withstand additional deformations until it failed at a displacement of 26 mm (point c). A photo showing the failure of one of the wedge bolts is given in Figure 11. During this test, the lateral deformation of the vertical bracket was negligible while its vertical deformation was almost equal to the reading of the MTS machine. This indicates that the bracket was moving as a one unit.

In test V2, the specimen behaved mainly in an elastic manner. A brittle concrete shear failure occurred at a load of 210 kN. The wedge bolts connecting the uplift bracket to the PC foundation behaved adequately during the test. Figure 12 shows a photo of the failed specimen. During this test, the lateral deformations of the vertical and uplift brackets were negligible. The vertical deformation of the uplift bracket was almost equal to the reading of the MTS machine while that of the vertical bracket was negligible. This indicates that the loading was transferred from the connector to the PC foundation through the uplift bracket.

Based on the results of tests V1 and V2, the two-piece and three-piece connectors could be modeled in finite element analyses as spring elements having a bilinear and a linear force-displacement relationship, respectively. The proposed force-displacement relationships are given in Figure 13. Additional tests are needed to confirm this model.

Cyclic Behaviour of PC Specimens

Two load tests (V3, V4) were conducted to investigate the cyclic behaviour of the three-piece connectors. Each specimen was subjected to a number of displacement cycles with an increase in the total displacement amplitude of 2 mm between successive cycles. The first four displacement increments were conducted twice to confirm that the concrete block is adequately fixed in position and that all LVDTs are functioning probably.

The two specimens behaved in a similar fashion and their ultimate behaviour was governed by concrete shear failure. Figures 14 and 15 show the load-deformation relationship for tests V3 and V4, respectively. The tensile capacity of both specimens was about 150 kN. As expected, the tensile stiffness was lower than the compressive stiffness mainly due to the difference in the load transfer mechanism. The load deformation cycles were pinched in shape demonstrating a low capability of energy dissipation. This is a typical performance of concrete specimens in shear, (Youssef and Ghobarah, 2001). A photograph showing the concrete shear failure that occurred in tests V3 and V4 is given in Figure 16.

The load-deformation results of tests V3 and V4 were analyzed to develop a simplified model that can be used in finite element analysis to predict the cyclic behaviour of the connectors. This led to the force-deformation curve shown in Figure 17. The dots shown illustrate the experimental envelope curves for both tests. The model is characterized by linear envelope curves in tension and compression. It was found that unloading from the compression branch (displacement d_2) would be aiming at displacement 0.69 d_2 on the X-axis while unloading from the tension branch (displacement d_1) would be aiming at a displacement 0.72 d_1 on the X-axis. The model is similar in nature to the beam-to-column joint shear model developed by Youssef and Ghobarah (2001) and need to be further verified using additional experiments.

Monotonic Behaviour of RC Specimens

Tests conducted on PC specimens helped to evaluate the performance characteristics of the helical pile connectors but these tests proved that concrete foundations are likely to fail in shear before reaching the connector ultimate capacity. For RC foundations, the reinforcement is expected to delay the concrete shear failure and thus might result in a change in the failure mechanism and hence the ultimate capacity. Further testing was required to evaluate the performance of the three-piece connector when installed in RC specimens. The results from these tests can be used to characterize performance of the connectors when helical piles are installed to retrofit reinforced concrete foundations. The test setup in this phase of the experimental work, was similar to that used for the PC Samples.

One monotonic test (V5) was conducted. The load-deformation curve of that test is shown in Figure 18. During the test, the connector did not show any signs of failure. The loading was stopped at a load of 240 kN as the load cell capacity was approached. The test proved that the reinforcement was effective in delaying the concrete shear failure.

Cyclic Behaviour of RC Specimens

Two vertical cyclic loading tests (V6 and V7) were performed using the same methodology explained before. The load deformation curves are shown in Figures 19 and 20. A low capability of energy dissipation characterizes the behaviour of the specimens. Failure was initiated in both tests by cracking in the weld connecting the stiffeners of the uplift bracket. This caused gradual decrease in the specimen strength until failure was observed in the uplift bracket. A photo showing the tearing of the uplift bracket is given in Figure 21. The failure occurred at a tensile load of about 170 kN in both tests. This means that the capacity of the three-piece connectors installed in RC specimens is 13% more than those installed in PC specimens.

Figure 22 shows a suggested model for the performance of the RC specimens. The model is characterized by a linear envelope in tension and compression. The point defining the unloading stiffness from these envelopes was obtained by examining the load displacement relationships shown in Figures 19 and 20. It was found that unloading from a displacement d_1 from the tension zone would be aiming at displacement 0.6 d_1 on the X-axis. Unloading from d_2 in the compression zone would aim at 0.65 d_2 on the X-axis.

Modified Three-Piece Connector

The cyclic tests described in the previous section showed that additional connector capacity could be obtained if the uplift bracket was strengthened. In this section, a trial strengthening technique is tested (V8). The modification involved welding two triangular steel plates to the ends of the uplift bracket, as shown in Figure 23. The testing was conducted in a similar manner to tests V6 and V7

The load deformation relationship is shown in Figure 24. In this test, the maximum load in tension was 184 kN and the specimen failed due to failure of the wedge bolts in shear. This means that the suggested modification, which could be easily fabricated, improved the cyclic tensile capacity by 8%. It is noticed that the specimen in that test was stiffer in tension than specimens in tests V6 and V7. This is attributed to the increase in the uplift bracket stiffness. On the other side, the stiffness did not change in compression. Further experiments should be made to ensure such enhancement in the performance.

Summary and Conclusions

In this paper, the performance of helical pile specialized connectors when subjected to vertical loading similar to the vertical loading component of an earthquake is assessed experimentally. These brackets have been attached to plain and reinforced concrete specimens using the same procedure implemented in the field. Also, a modification to the connector design is suggested and tested. Both monotonic and cyclic loading tests were performed. The following conclusions were drawn.

a. Monotonic Tests:

1. PC foundations: The two-piece connector tensile capacity is about 51 kN. This capacity has been reached at a displacement of 20 mm. This has been followed by shear failure of the two wedge bolts connecting the vertical bracket to the concrete specimen.
2. PC foundations: The three-piece connector tensile capacity is about 210 kN and has been associated with a shear failure of the concrete specimen. The connector has survived the test without any damage.
3. The two-piece connector and three-piece connector can be modeled as a spring elements. The proposed force-displacement relationships to be used for each of them are shown in Figure 13.

b. Cyclic Tests:

1. PC foundation: the tensile cyclic capacity is about 150 kN, about 71% from the monotonic capacity. This is mainly due to the degradation of the shear stiffness of the concrete specimen under the applied cyclic load.
2. PC foundation: the compressive cyclic capacity is about 200 kN, about 133% higher than the cyclic tensile capacity. This is mainly due to the difference in the load transfer mechanism.
3. PC foundation: Shear Failure in the concrete specimens was observed. The nominal geotechnical capacity of helical piles ranges between 200 kN and 1000 kN, i.e., the concrete failed at 15% to 75% of the piles capacity. Thus, the seismic capacity of the helical pile foundation will be governed by the ability of the concrete foundation to support the seismic load transmitted from the connector. To utilize the full geotechnical capacity of the screw pile, either reinforced concrete foundations or retrofitted concrete foundations should be considered.
4. RC foundations: The concrete foundation has survived the test without any damage and failure was initiated by cracking in the weld connecting the stiffeners of the uplift bracket. Failure load was about 170 kN in tension.
5. RC foundations: The helical pile connector was modified by welding two triangular steel plates to the ends of the uplift bracket, as shown in Figure 23. The modified connector survived the test without damage and failure was initiated by shear failure of the wedge bolts at a load of 184 kN in tension. Increasing the number or size of bolts is expected to result in a higher failure load.

4. The three-piece connector can be modeled as a spring elements. The proposed force-displacement relationships to be used are shown in Figures 17 and 22 for connectors installed in PC and RC foundations, respectively.

The conclusions driven in this study are based on a limited number of tests. Additional tests are required to confirm these results.

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Table 1 Proportions of Concrete Mixtures Used per Cubic Meter of Concrete

	PC	RC
Cement Content (kg)	380.00	364.00
Silica Fume (kg)	--	36.00
Water (kg)	167.20	132.00
Fine Aggregate (kg)	760.00	780.00
Coarse Aggregate (kg)	1107.00	1150.00
Super-plasticizer (litres)	--	4.20

List of Figure Captions

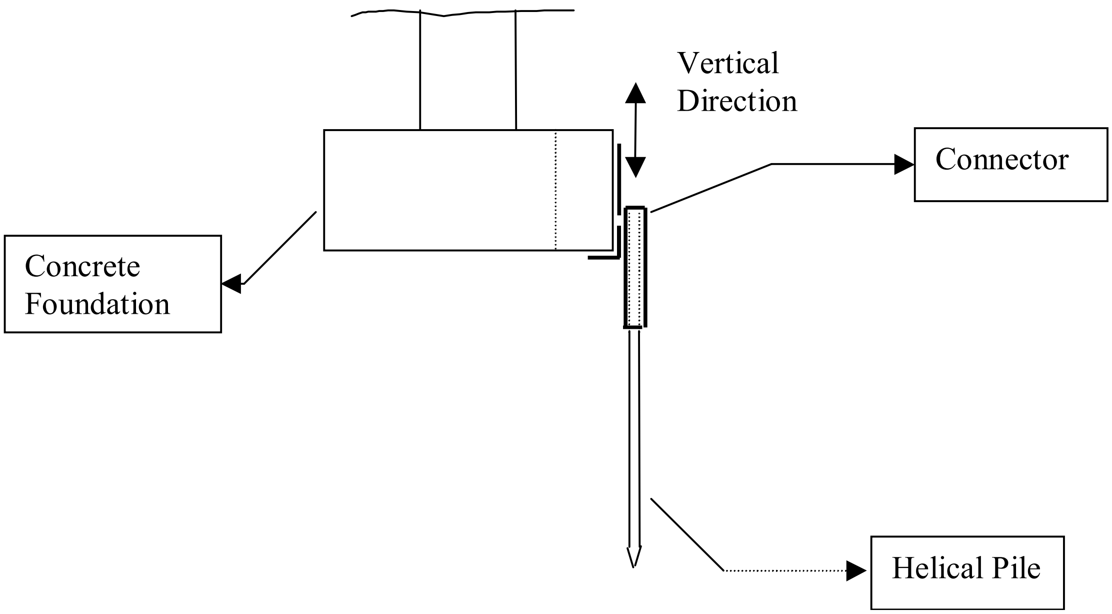

Figure 1 Typical Helical Pile After Installation

Figure 2 Two Reinforced Concrete Specimens

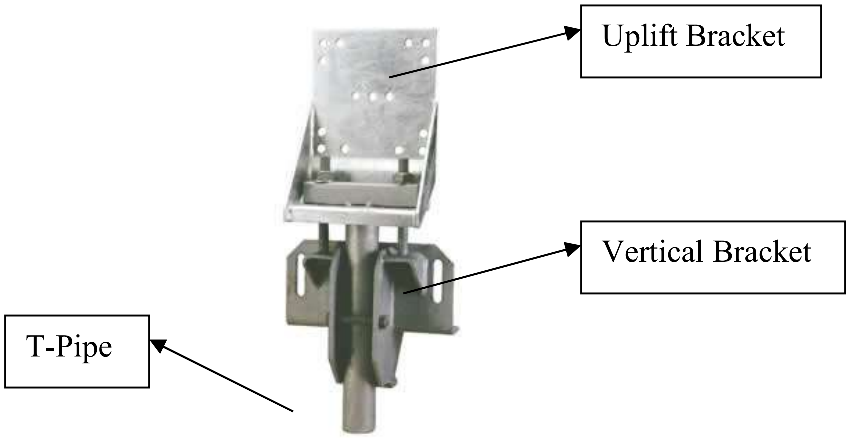

Figure 3 Helical Pile Specialized Connector

Figure 4 Wedge Bolt

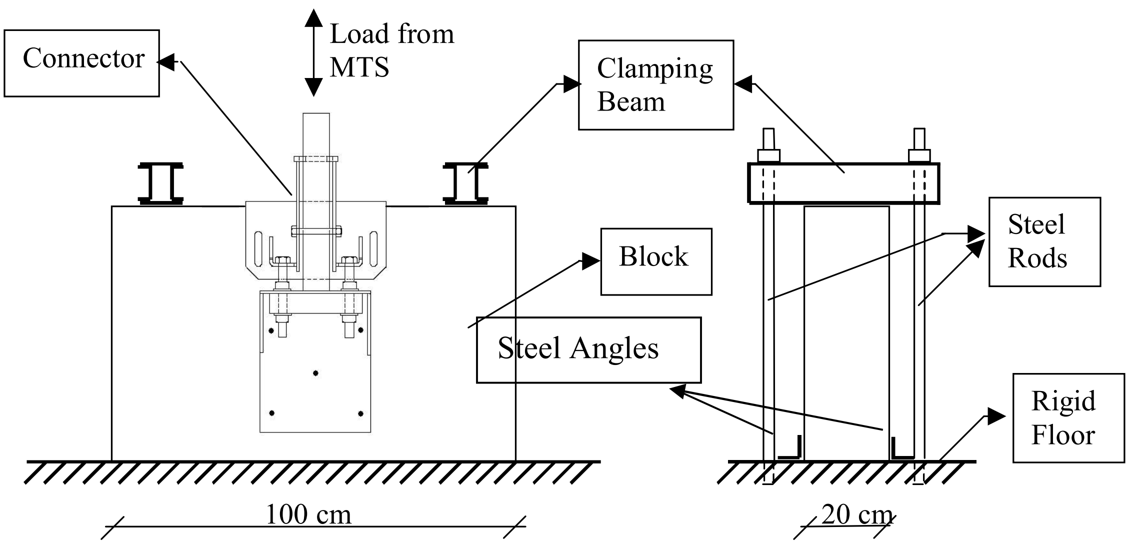

Figure 5 Test Setup

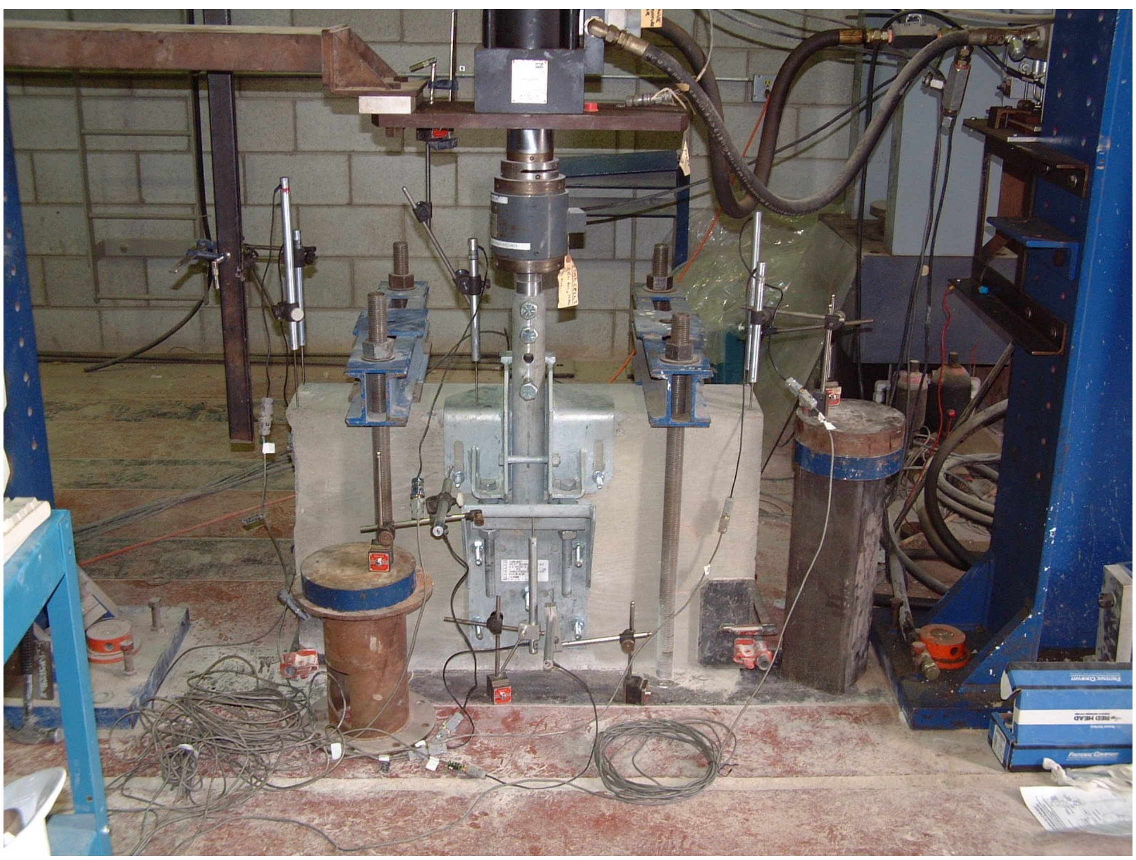

Figure 6 Photograph of the Test Setup

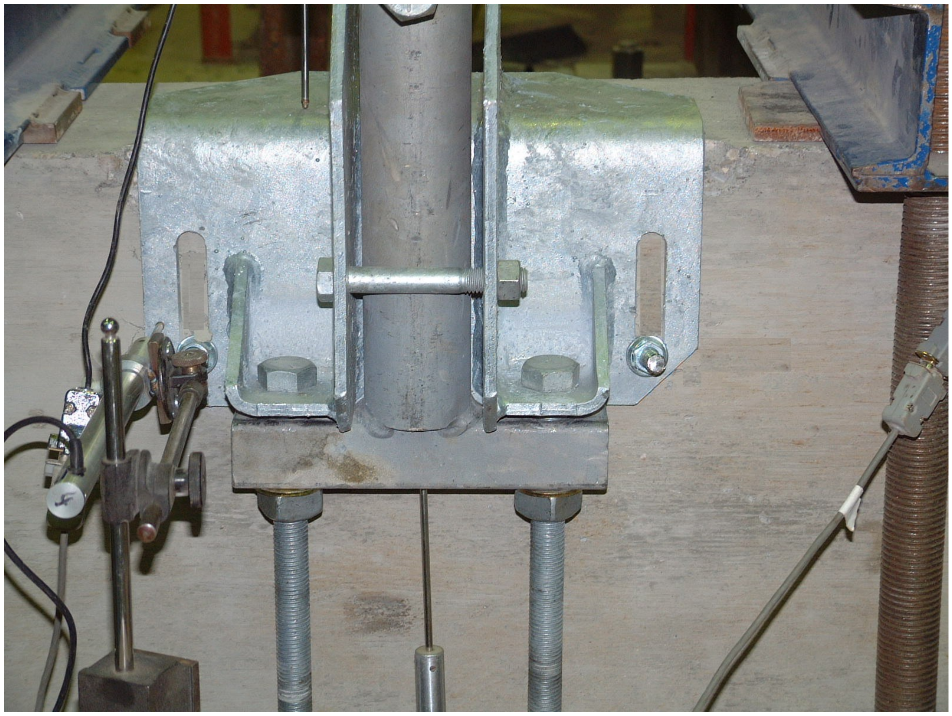

Figure 7 Monotonic Test of the Two-Piece Connector (V1)

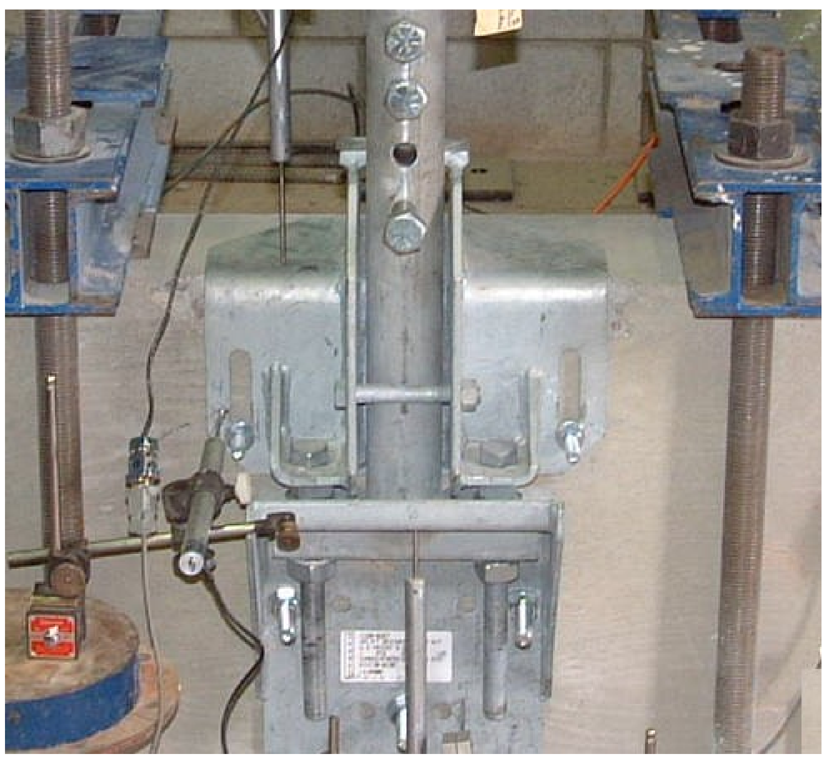

Figure 8 Monotonic Test of the Three-Piece Connector (V2)

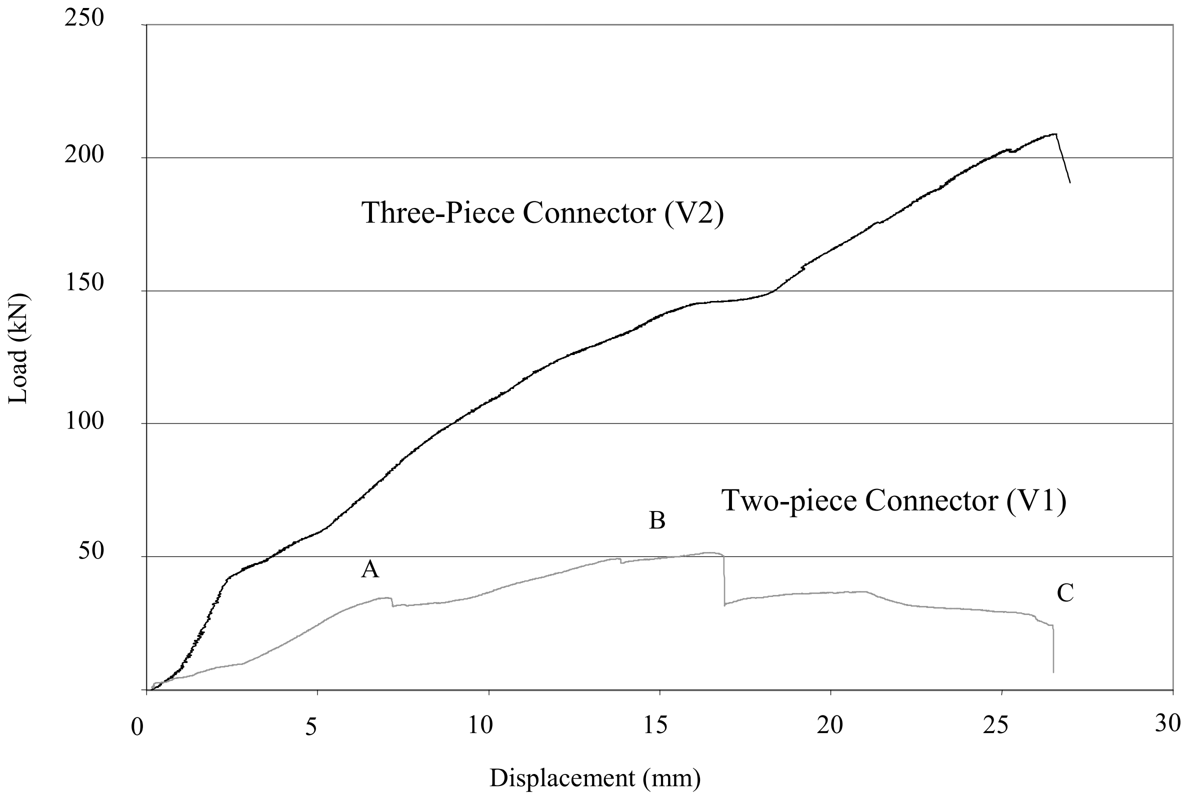

Figure 9 Load-Deformation Relationships (PC Specimens)

Figure 10 Cracks Observed at Displacement of 7.5mm (Test V1)

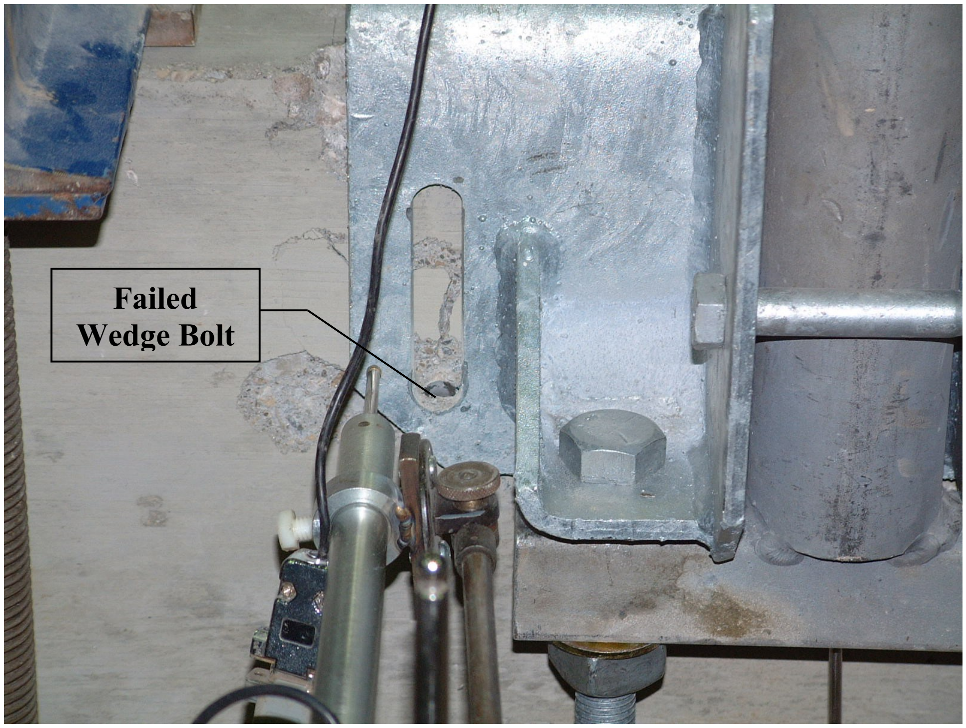

Figure 11 Shear Failure of a Wedge Bolt (Test V1)

Figure 12 Shear Failure of Plain Concrete Block (Test V2)

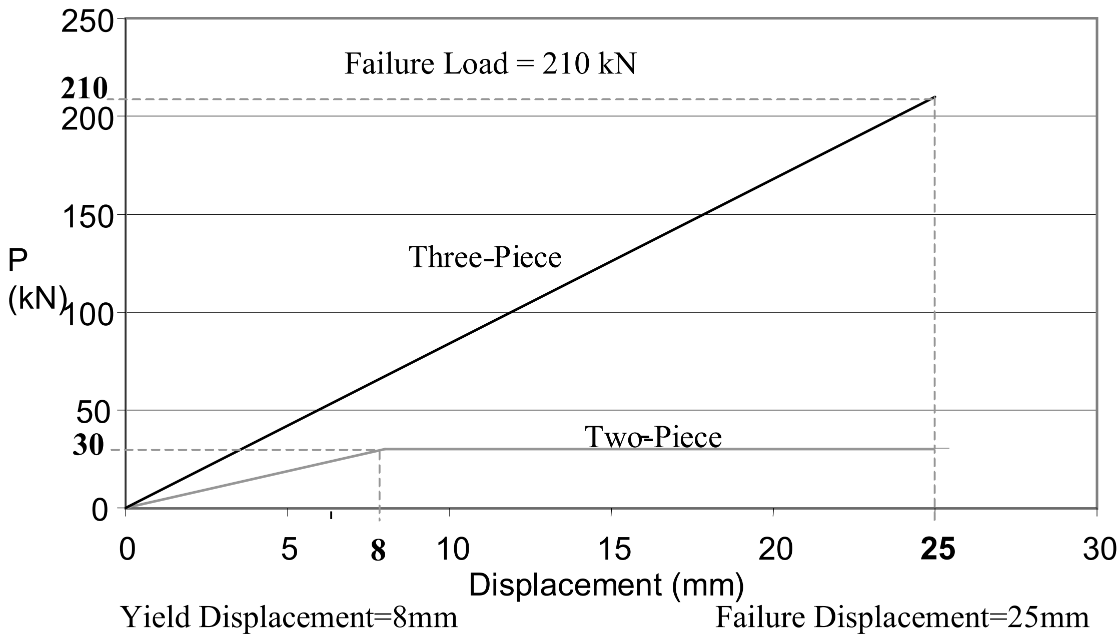

Figure 13 Modeling the Monotonic Behaviour of the Two-Piece and Three-Piece Connectors

when Installed in PC Foundations

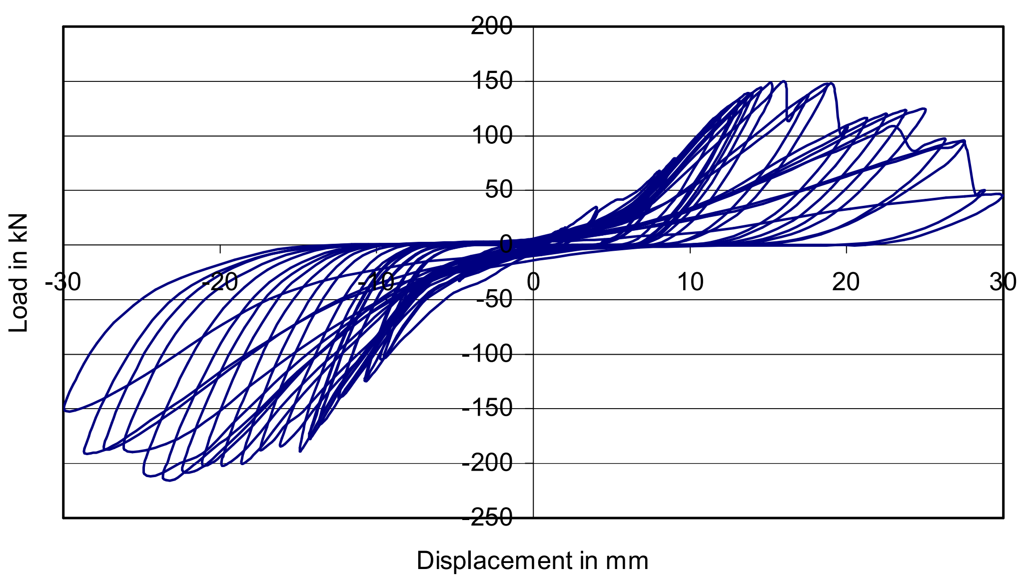

Figure 14 Cyclic Load Deformation Relationship (Test V3 – PC Specimen)

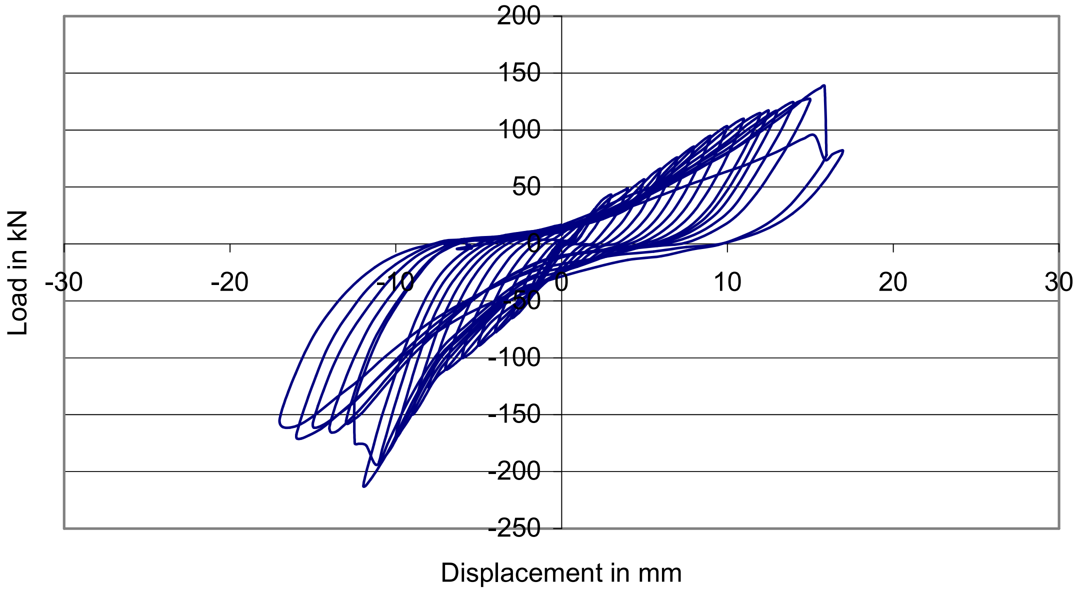

Figure 15 Cyclic Load Deformation Relationship (Test V4 – PC Specimen)

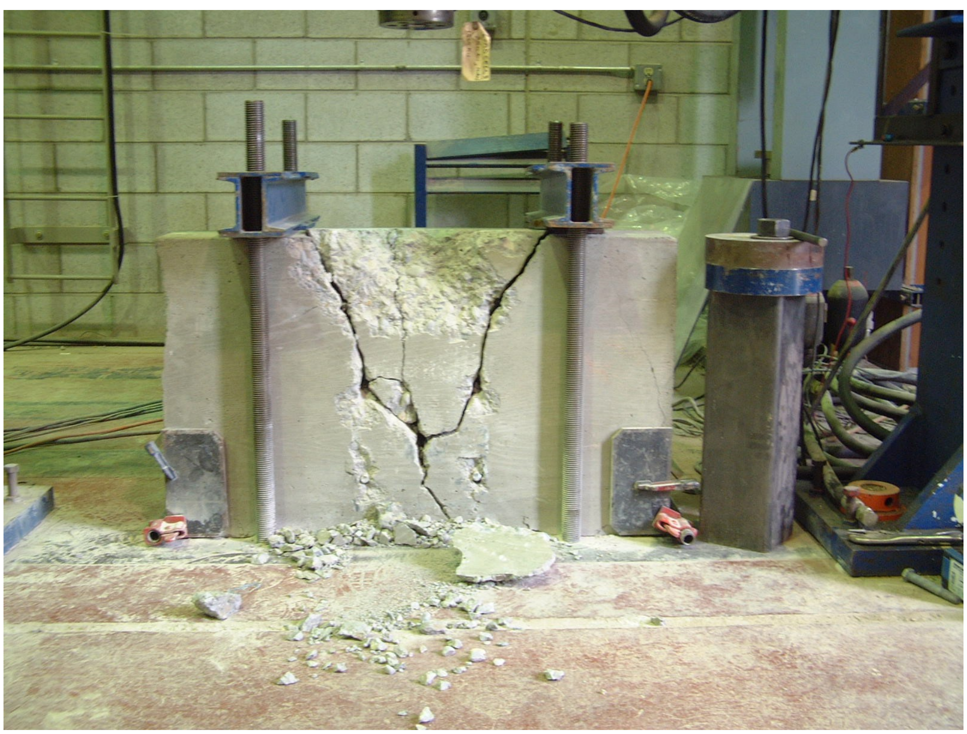

Figure 16 Shear Failure of Plain Concrete Block (Tests V3 and V4)

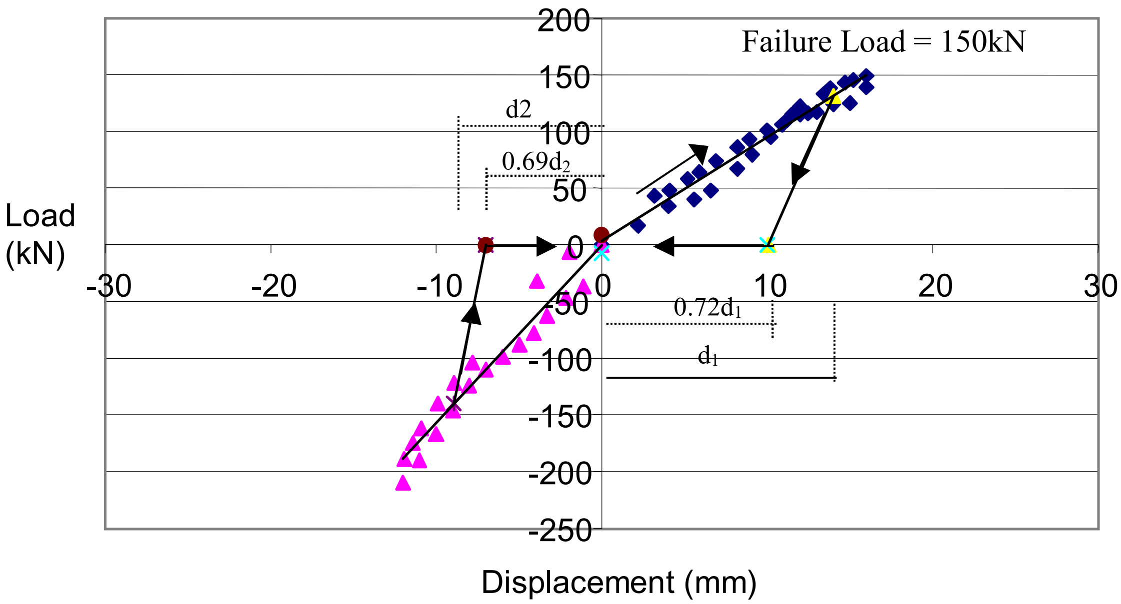

Figure 17 Model for Cyclic Behaviour of Three-Piece Connector in PC

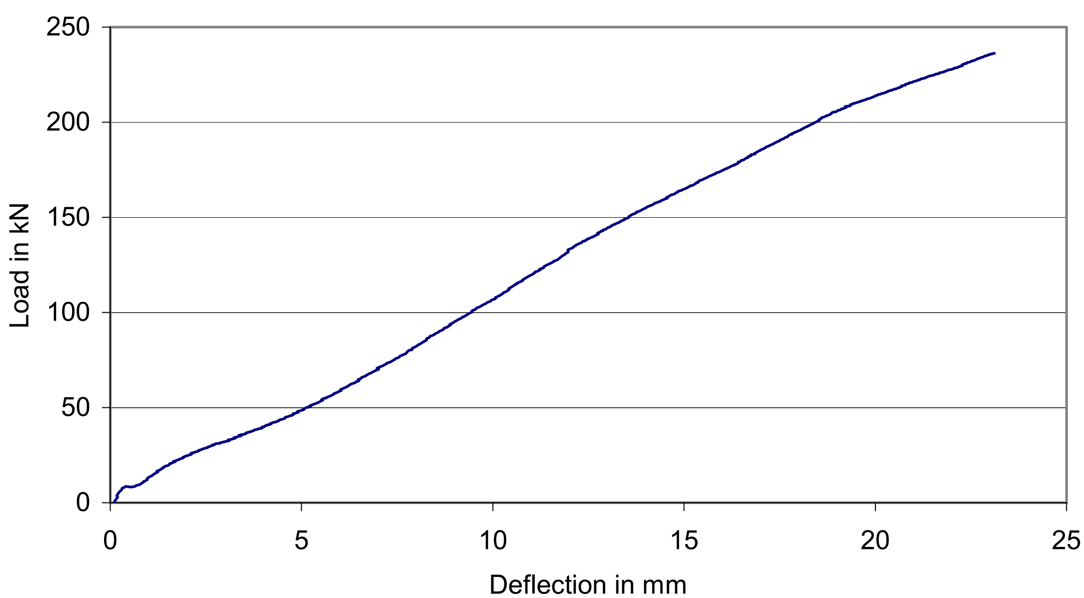

Figure 18 Load-Deformation Relationship for Test V5 (RC Specimen)

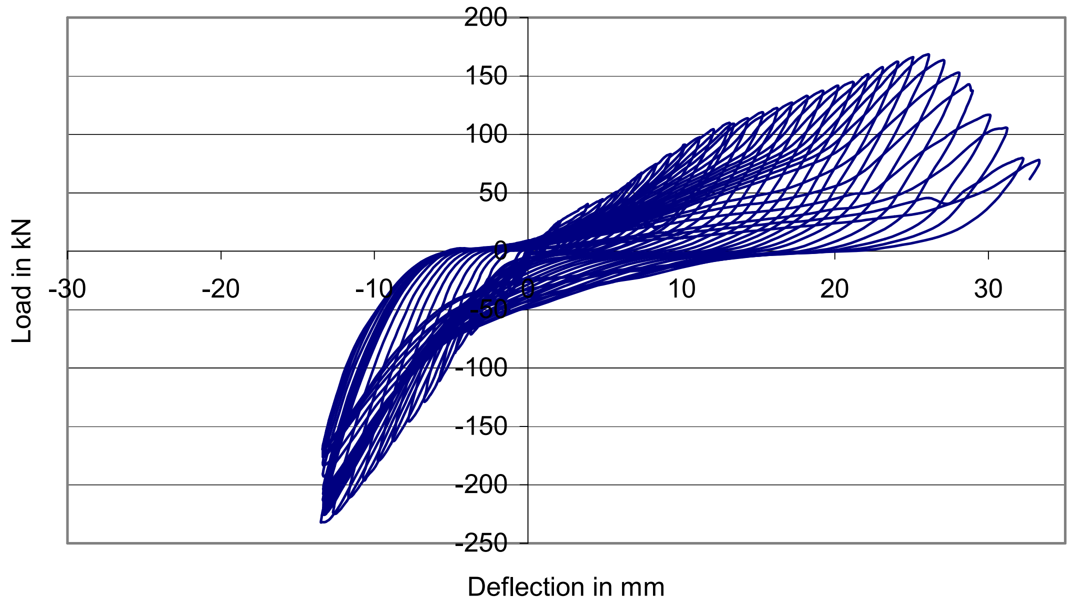

Figure 19 **Cyclic Load Deformation Relationship (Test V6 – RC Specimen)**

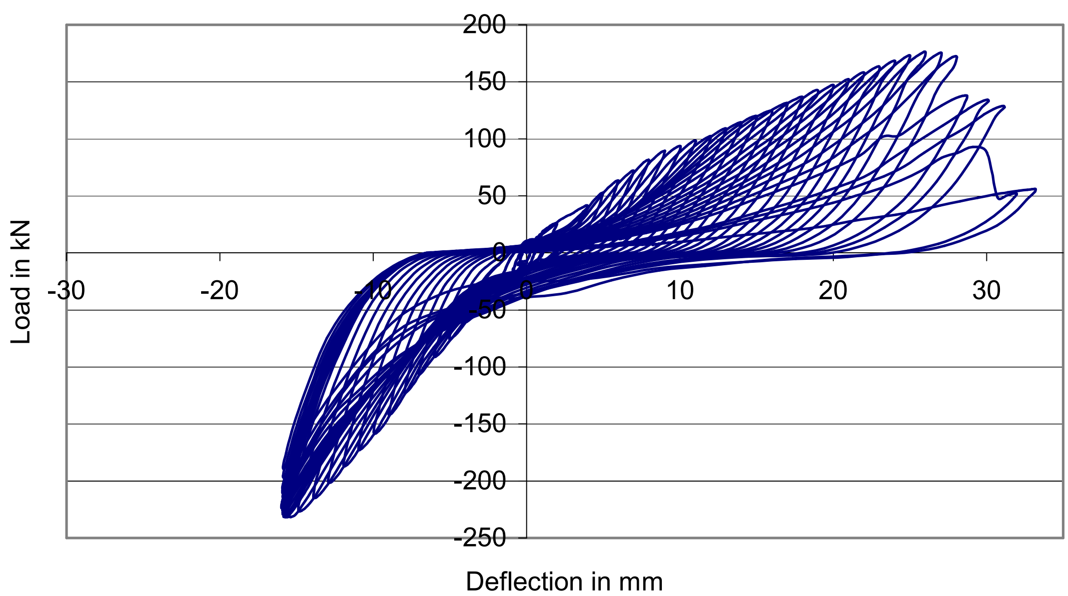

Figure 20 Cyclic Load Deformation Relationship (Test V7 – RC Specimen)

Figure 21 Failed Uplift Bracket during Tests V6 and V7

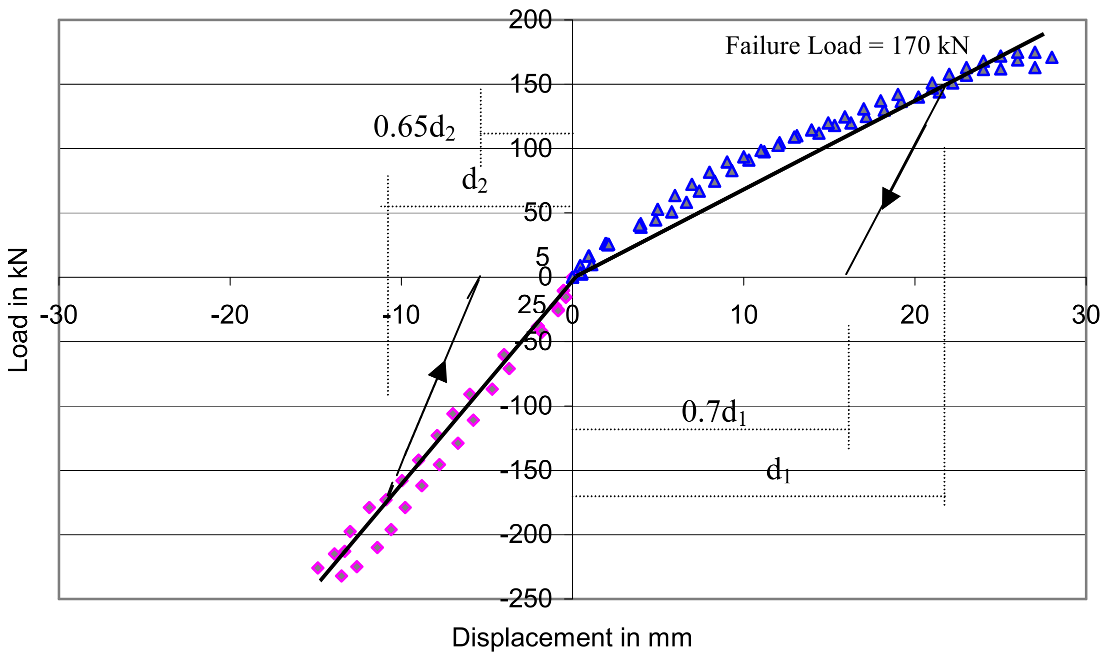

Figure 22 Model for Cyclic Behaviour of Three-Piece Connector (RC Specimens)

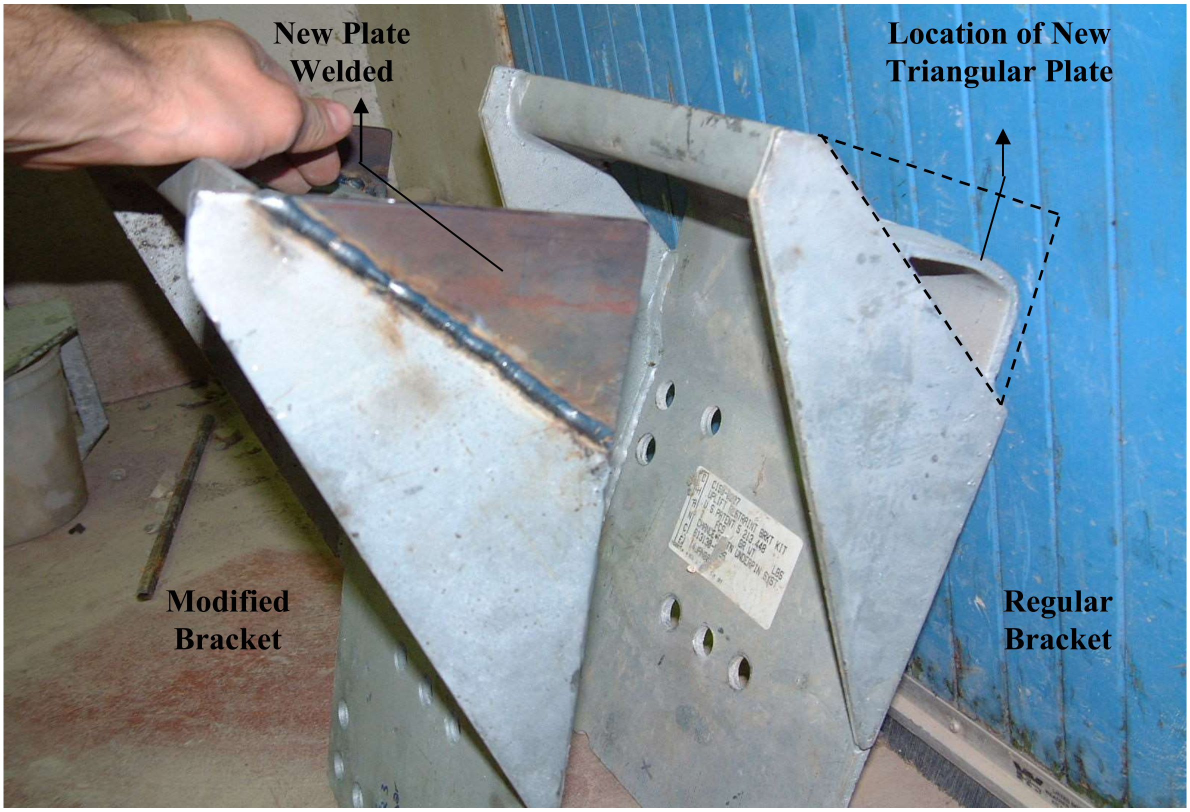

Figure 23 Modified and Regular Uplift Brackets

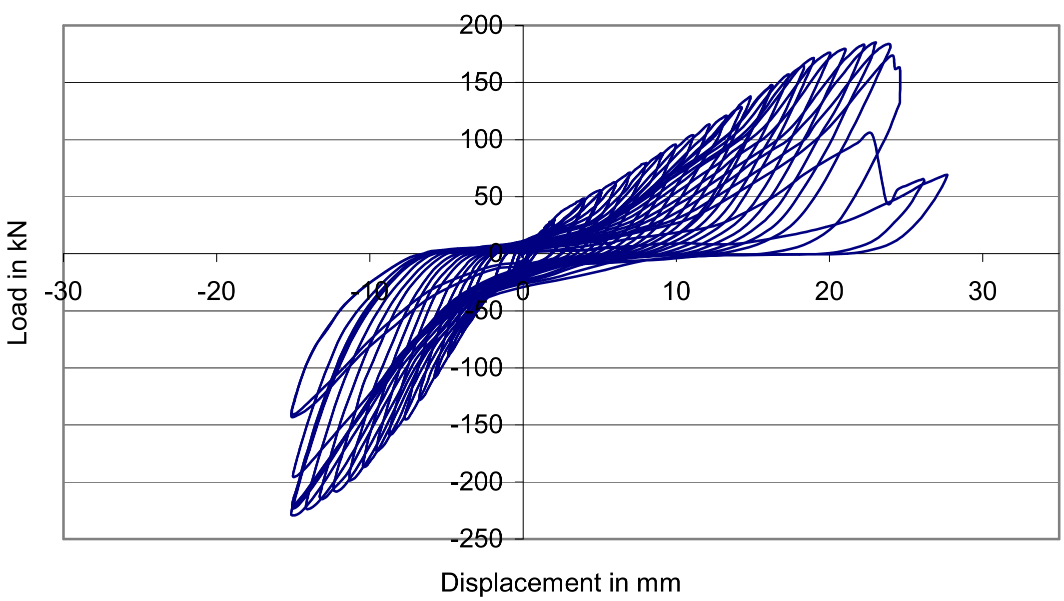

Figure 24 **Cyclic Load Deformation Relationship (Test V8 – RC Specimen)**