SEISMIC QUALIFICATION TESTING OF CONCRETE EXPANSION ANCHORS TO NUCLEAR STANDARDS

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ABSTRACT

Expansion anchors are widely used in Nuclear Generating Stations (NGS) and major civil structures. These post-installed expansion anchors are considered useful since they allow the civil concrete work to proceed and be completed without the requirements for the precise knowledge of the exact locations of small equipment, piping, cable trays etc. Expansion anchors are also required for any design changes, improvements and retrofit work after the nuclear generating station has gone into service.

A large number of unique seismic qualification tests were performed on different types of expansion anchors to determine their seismic capabilities. These tests followed the requirements of the Canadian CSA N287 standards as well as the ASTM E 488 standard. All sizes for these expansion anchors ranging from 1/4" to 1 1/4" have undergone this seismic qualification testing.

Strategically designed concrete blocks were manufactured to receive each expansion anchor. The anchors were installed according to the anchor manufacturer instructions and the installation was consistent with construction practice. Each anchor has been subjected to four different types of tests covering static, dynamic, tension and shear loading. Each test has been repeated three times to obtain statistically reliable test data. The dynamic cyclic loads applied represented a severe earthquake that is much higher than the Design Basis Earthquake (DBE). The seismic testing qualification program involved 300 tests. The results of the testing program are obtained for each type of anchor.

Results obtained from these tests confirm that these types of expansion anchors have maintained their tension (pull-out) and shear capabilities following a severe seismic shaking. In several cases the effect of the seismic shaking was found to be somewhat beneficial since it has resulted in setting the expansion mechanism of the anchors. As a result some anchors were able to withstand slightly larger loads by comparison to anchors that have not been subjected to seismic shaking.

INTRODUCTION

Expansion anchors are widely used in Nuclear Generating Stations (NGS). For heavy equipment loads it is considered more appropriate to use strategically located Embedded Parts (EP). Once the civil concrete work is completed, one has to utilize post-installed anchors for anchorage to concrete. The seismic capabilities of expansion anchors are sometimes questioned since they rely on expansion mechanism for achieving holding power. The effect of the seismic cyclic loading on this holding power mechanism is not known or understood. Seismic design has been routinely performed conservatively with sometime excessive simulation of the seismic loading. In addition recent codes have put forward the idea of anchorage ductility as a desirable feature in the design. This could lead to the situation that if the seismic loading is chosen conservatively that the types of expansion anchors in use today by the construction industry may be considered disqualified. A realistic simulation for the seismic effects on expansion anchors combined with a comprehensive testing program are essential to resolve this crises. The resistance of expansion anchors and their suitability for the type of loading depend on several variables such as concrete strength, embedment depth and edge distance. The anchor capacity has to be verified by testing. This paper summarizes the seismic qualification testing and results for various sizes of expansion anchors. The overall objective of the seismic qualification program for the expansion anchors is to establish the capability of the expansion anchors to maintain their load carrying capacity following an earthquake that is larger than the Design Basis Earthquake (>DBE). The basis for the seismic qualification was to test the expansion anchors under static loads and compare the results with similar tests on anchors that have been subjected to the dynamic loads as specified by nuclear codes. A total of 25 different sizes of these expansion anchors have been tested for Static Tension and Static Shear and Dynamic Tension and Dynamic Shear. The tests were all performed at McMaster University Applied Dynamics Laboratory (ADL). Representatives from the anchor suppliers participated in the installation of the anchors to ensure that the work has been performed to the supplier's procedures. Nuclear Quality Assurance (QA) requirements for the testing program were provided by an independent testing laboratory. The objective of the current paper is to describe the methodology and approach for the seismic qualification testing of different types of expansion anchors.

SCOPE OF THE TESTING

Tests have been conducted on single anchors. Four different types of anchors were tested. These reflected the types of anchors widely used in the nuclear industry today. The following are the types of anchors included in the test program:

1. Philips red head self drilling
   1/4 3/8 1/2 5/8 3/4" (total of 5 sizes)

2. Philips Red head Wedge
   1/4 3/8 1/2 5/8 3/4 7/8 1 1 1/4" (total of 8 sizes)

3. Hilti Kwik bolt II
   1/4 3/8 1/2 5/8 3/4 1" (total of 6 sizes)

4. Hilti heavy duty HSLG (Metric)
   M8 M10 M12 M16 M20 M24 (total of 6 sizes)

SPECIFICATION AND NUCLEAR STANDARDS

Static load testing and testing for seismic qualification of the Expansion Anchor bolts were conducted according to the following applicable standards and specifications:
- CSA N287.2-M91 Material Requirements for Concrete Containment Structures for CANDU Nuclear Power Plants.
- CAN3-A23.1-94 Concrete Materials and Methods of Concrete Construction.
- ASTM E 488 Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements.

In addition detailed Technical Specifications and testing procedures were developed to implement the above standards. This included a detailed testing and inspection plan by an independent testing laboratory. Quality Program Requirements were followed with detailed test specifications, records log book and equipment calibration control. A quality inspection and test check lists were prepared by the independent testing laboratory to address the CAN3 CSA Z299.3 requirements. Access to the test facilities was provided to the independent test laboratory Operations staff to perform surveillance and verification.

TEST PROGRAM

The anchors were installed in concrete blocks that were designed and built specifically for this test program. Four tests: static tension, static shear, dynamic tension and dynamic shear were performed for each size of each type of anchor bolts. Three anchors were tested per size and the three results obtained were averaged to account for statistical uncertainty. A test program records logbook was maintained and made available for an independent test laboratory for verification.

Test Specimens

The preparation of the test specimens involved the design and construction of concrete blocks and the installation of expansion anchors in the concrete blocks. Un-reinforced concrete blocks were designed and constructed, one for each anchor bolt. The blocks were designed to the following dimension criteria (ASTM E 488):
The depth of the test block is determined according to the ASTM E 488 as 1.5 the embedment length of the anchor bolt.
For standard bolt embedment installation, all applicable specifications and codes agree that the effective stress area is defined by the projected area of stress cone radiating towards the concrete surface from the bearing edge of the anchor at 45 degrees. This translates into a minimum block dimension without bearing surfaces of twice the embedment length of the anchor. The Nuclear Code N287.3 recommends 45 degrees stress cone (Clause 15.4.2 (b)). The CSA standard N287.2, Clause 11.3 recommends that ASTM E 488 standard may be used as a guideline for preparing the test procedures and test equipment which again specifies block dimension of twice the embedment length of the anchor. The most comprehensive specifications on the minimum block dimensions is that given by the ASTM E 488 Clause 6.4.2 in the form of the following table:

Embedment (E)		Minimum Edge Distance
Shallow	$< 6.0\ d$	1.75 E
Standard	$6.0\ d < E < 8.0\ d$	1.00 E
Deep	$>8.0\ d$	0.75 E

Where d is the anchor diameter.

The minimum width and length of the concrete blocks were determined on the basis of the minimum distance or edge test frame (location of the bearing support) as given by the above ASTM E 488 table.
The dimensions of the blocks were chosen to satisfy ASTM E 488 requirements. These two standardized block types were chosen as follows:

- Block type A: 533 x 305 x 152 mm (21 x 12 x 6 inches) for anchor bolt sizes up to 1/2" or M12
- Block type B: 533 x 410 x 305 mm (21 x 16 x 12 inches) for anchor bolt sizes up to 1 1/4" or M24

Forms for pouring the individual blocks were prepared of practical sizes of 4' x 8' x 6" and 4' x 8' x 12" for Block types A and B respectively. Pouring concrete was done in several stages. The blocks were equipped with steel wire in the form of a loop for easy lifting and handling.

In each stage of the first three stages, four 4' x 8' x 6" boxes were poured giving 56 blocks type A and four 4' x 8' x 12" boxes were poured giving 40 blocks type B. In the last (fourth) stage, one 4' x 8' x 12" box and two 4 x 8 x 6" boxes were poured. This concrete pouring program produced 196 type A and 130 type B blocks.
The blocks were made of 20 MPa concrete per CSA N287.2 requirements. The concrete was specified to have a slump between 70 and 85 mm. The maximum aggregate size is specified as 20 mm that is the same aggregate usually specified in regular concrete used in construction.
During each stage of pouring, 15 cylinders were poured and tested, 12 in compression (3 after 28 days, 3 after 35 days, 3 after 42 days and 3 after 49 days) and 3 for splitting tests (tension tests) after 28 days to obtain reliable data on concrete strength.
The concrete surface was covered with wet burlap and then covered with a sheet of plastic material for a minimum of three days. The burlap was wetted twice a day. After the initial curing, the forms were removed and the surface of the blocks was kept moistened for 7 days.
All the concrete blocks were numbered and identified by size, pouring lot and date of pouring according to the identification system outlined in Table 1, and the anchor identification once installed. Test records are traceable to the test piece using the concrete block/anchor identification.

Anchor Installation

The anchor size, embedment requirement, material specifications and installation procedures as recommended by the manufacturer were used. All the anchors were marked and identified with a tag according to the identification system outlined in Table 1. The anchor identification was added to the concrete block identification once installed. The size of the drilled hole, embedment requirement and installation procedures were those recommended by the anchor supplier. Representatives of the anchor supplier participated actively in the anchor installation process in order to ensure adherence to recommended procedures.

For the Hilti HSLG anchor system, two alternative installations are allowed; the standard installation with the sleeve within the base plate and a "Flush" type installation with the sleeve within the concrete. In this testing program, a sleeve was installed flush with the concrete surface. This installation procedure does not affect the tensile strength of the anchor but is expected to lower the shear capacity.

In the testing program, the tightening torque used were those recommended by the anchors supplier to ensure that the expansion mechanisms of the anchors were set to work. The manufacturer's recommendations typically produce a tension of approximately 45% of the minimum specified ultimate tensile strength of the anchor. The application of the torque was performed as follows:

- Apply the torque as per the supplier's installation Catalogue.
- Remove the torque by loosening the nut. Install the test fixture required for the test.
- Reapply the torque but only to 50 % of the manufacturer's value. This assumes that the other 50 % of the pretension is lost as a result of load/torque relaxation during the service life of the plant.

Test Equipment

The equipment used in the testing program included:
Static tension and static shear test fixtures. These test fixtures were constructed as per ASTM E 488. As an example Figure 1 shows the Static tension fixture.
Dynamic tension and shear test equipment using an MTS actuator with maximum rated load capacity of 50,000 lb. As an example Figure 2 shows the dynamic shear test fixture.
Computer controlled Data acquisition system
Torque wrench
Drills and other Standard hand tools
The loading fixtures were fabricated for the tension and shear tests. The loading plate hole is taken 1.5 ± 0.75 mm greater than the anchor bolt diameter.

A sheet of plastic material 0.5 mm thick was installed between the plate and the concrete surface in the static and dynamic shear tests. This is an ASTM E 488 requirement to provide for a smooth sliding surface. This ASTM testing practice is expected to lead to lower shear capacity by lowering the friction forces in comparison to actual installation.
The bearing support of the equipment was designed to be beyond the limit specified by the embedment versus the distance to edge or test frame table of ASTM E 488.
The thickness of the loading plates were chosen such that it will not exceed the maximum allowed for the bolt with due consideration to the contact area. The test loading plate contact area is calculated on the basis of the following:

Bolt Diameter Range (mm)	Contact Area
<10	50 - 80 cm^2
10 to 16	80.01 - 120
16 to 22	120.01 - 160
22 to 30	160.01 - 260

Equipment Calibration

The load cells of the test equipment were calibrated using a calibrated 10,000 lb. proving ring. The following equipment were calibrated before and after the expansion anchor test program:
- Load cells of the static and dynamic test equipment
- LVDT measuring devices
- Torque wrench

The equipment is identified by type, serial number, capacity and calibration procedure. This information is included in the test reports and was subject to inspection by an independent test lab.

METHOD OF TESTING AND LOAD APPLICATION

Static Load Application

The static tension and the static shear loading were applied independently in separate tests. The objective is to test for pure tension and for pure shear with every attempt made to avoid combined tension and shear loads. In the static tests, small initial load was applied (approximately less than 5% of the estimated maximum load capacity of the anchor) in order to bring all members into full bearing. Monotonically increasing load was then applied. The continuous load application was maintained at the rate of approximately 10 % of the ultimate anchor capacity per minute. The total test time was kept at a minimum of 2 min.
The static testing produced anchor bolts load capabilities that were then used to set up the testing loading levels to be used in the follow-up dynamic (seismic) loading testing.

Dynamic Load Application

The dynamic load was applied at a frequency of 5 Hz in accordance with the suggested requirements of CSA N287.2. This represents the case of resonance with typical nuclear structures and equipment.

a) Dynamic Tension Testing:

The following dynamic tension loading sequence was considered in the testing as suggested by CSA N287.2:
- 30 cycles at 53% F_y
- 30 cycles of 45% F_y
- 80 cycles of 30% F_y
- 200 cycles of 15% F_y

Considering that expansion anchors are not necessarily ductile in nature the maximum cyclic load level for the seismic test (T) was determined based on the higher of the following loads:

a) The load reported by the supplier (as the Ultimate Failure Load) divided by a Factor of Safety of four (4.00)

b) 53% F_y ; where F_y is the tensile yield strength of the anchor bolt based on the nominal yield stress level given by the supplier and the "stress area" of the bolt in tension as suggested by CSA N287.2 Standard.

If the value as determined under (b) exceeds the Ultimate Failure Load by the supplier (or from the tests), the load corresponding to 0.53 of the Ultimate Failure Load is used in lieu of (b)

The dynamic tension loading program was applied in conformance with the code specified loading sequence shown in Figure 3. The actual values of the maximum ordinates used in the dynamic cyclic loading program (T) are derived by the procedure as explained before.

b) Dynamic Shear Loading:

The following dynamic Shear loading sequence was considered in the testing as suggested by CSA N287.2:
- 30 cycles at 16% F_y

- 30 cycles of 12% F_y
- 80 cycles of 8% F_y
- 200 cycles of 4% F_y

The maximum cyclic load level for the seismic test (S) is determined based on the higher of the following loads:

a) The load reported by the supplier (as the Ultimate Failure Load) divided by a Factor of Safety of four (4.0)

b) 0.16 F_y ; where F_y is the shear yield strength of the anchor bolt based on the nominal yield stress level given by the supplier and the "Gross Area" of the bolt in shear as suggested by CSA N287.2 Standard.

In the case where the specified design load in shear is larger than 16% F_y, the design load will be used in the shear test instead. The design shear load will be applied for the first 30 cycles, the second 30 cycles at 0.75 the design load and then 80 cycles at 0.50 design load followed by 200 cycles at 0.25 the design load.

Hole clearance during a seismic test may be selected according to CSA N287.2 or ASTM E488 Standards. It was concluded that the CSA N287.2 clearance requirement represents the case of a "loose clearance" while ASTM requirement represents the case of an average or "normal clearance". Ideally, the required hole clearance should depend on the fastener diameter; being small for small diameter bolts and large for large diameter bolts. CSA N287.2 states that "ANSI/ASTM Standard may be used as a guideline for preparing the test procedures and test equipment for the tests required by Clause 11.3. As a result, the implementation of ASTM E 488 Standard for the hole clearance of 1.5 ± 0.75 mm is considered acceptable.

The dynamic shear loading program was applied in conformance with the code specified loading sequence shown in Figure 4. The actual values of the maximum ordinates in the dynamic cyclic loading program (S) are derived by the procedure explained before.

Data Measurement

For each test, the following data was recorded:

- The applied load as measured by the load cell.
- The deformation as measured by Linear Variable Displacement Transducer (LVDT) positioned to measure the movement of the anchor relative to the concrete block.
- Failure load or the maximum load sustained by the anchor.
- Mode of failure.

The load and deformation measurements were recorded by computer controlled data acquisition system.

Failure Criteria and Failure Modes

The expansion anchor shall be classified as fully seismically qualified when 3 consecutive test specimens, after successfully surviving the cyclic tensile or shear loading, all withstand a static tensile or shear load similar to the average failure load of the static tests without cyclic loading. Failure of the bolt will be considered to be reached if the bolt slips a distance of 6.35 mm or (0.25").

Failure of the bolt expansion anchor system is considered to be reached if the bolt fractures or slips; or if the concrete block cracks. The encountered failure modes were classified in six groups. Each of these identified failure modes has been illustrated by a typical picture.

Failure Mode Designation	Description	Figure Number
A	Bolt yield or fracture	Figure 5
B	Anchor pull-out (slip)	Figure 6
C	Anchor slip followed by block fracture	Figure 7
D	Cone in tension	Figure 8
E	Radiating cracks	Figure 9
F	Bearing failure then block failure (split)	Figure 10

The behavior and failure modes of expansion anchors depend on the relative strengths of the anchor and the concrete. For this reason, it is recognized that expansion anchors may not behave in a ductile manner and as a result higher safety factors against failure are required in the design (e.g. 4.0).

ANALYSIS AND TEST RESULTS

The results of the concrete cylinder tests of the four stages of concrete pouring are obtained by testing three specimens at 7 days, 28 days, 35 days and 42 days. These results showed typical increase in concrete strength with time. These results were used to give a good indication of the concrete strength during the period of the anchor testing.

For each expansion anchor size, the results were obtained for static tension, static shear, dynamic tension and dynamic shear. Load-deformation measurements were obtained and for each anchor size four graphs are plotted for each type of test;

Static Tension, Static Shear, Dynamic Tension and Dynamic Shear. Since the tests were repeated for three anchors, three curves were obtained for each type of test. The failure load, the displacement at failure and the failure mode are also obtained. Tabulated results for the static tests can be compared with tabulated results for the dynamic tests. The failure dynamic loads are obtained after the anchor bolt was subjected to the dynamic cyclic tension or shear in accordance with the minimum suggested requirements of CSA N287.2 as outlined before.

CONCLUSIONS

Seismic qualification testing of expansion anchors was conducted in accordance with the procedures of the applicable standards and specifications including ASTM E 488 and CSA N287.2. From the results of the test program, the following conclusions are arrived at:

1. In general the failure capacities of all anchors in tension were higher or marginally below the supplier's specified ultimate load. Slight differences were observed for the large anchors.
2. In general the failure capacities for shear were higher than the manufacturer specified ultimate loads for anchors up to 12 mm. The failure capacities were lower than the supplier's specified ultimate load for the larger diameter anchors. Factors which may have contributed to the conservative estimate of the anchor ultimate shear load are: a) the use of 0.5mm thick sheet of plastic placed between the concrete surface and the steel shear fixture b) Special care was exercised to ensure that the concrete strength is as close as possible to 20 MPa. c) The manufacturer has utilized reinforcement for the concrete or significant large size slabs for the shear testing.
3. For all the tested anchors, failure loads were found to be much higher than the specified design loads. The lowest value observed was the shear capacity of the 1" Kwik anchor bolt where the anchor sustained about 1.80 times the design load. The design load was taken as one fourth of the supplier's specified ultimate load as per normal practice.
4. After successfully surviving the cyclic tensile or shear loading, anchors withstood a static tensile or shear load similar to the average failure load of the static tests without cyclic loading and as a result these anchors are classified as seismically qualified.
5. The comprehensive testing program and experience presented in this paper should be useful for seismically qualifying new types of anchors since the seismic qualification requirements are considered more realistic.
6. Results obtained from these tests confirm that these types of expansion anchors have maintained their Pull-out and Shear capabilities following a severe seismic shaking. In several cases the effect of the seismic shaking was found beneficial since it resulted in anchors being able to withstand larger loads by comparison to anchors that have not been subjected to seismic shaking.

Table 1 Expansion Anchor and Concrete Blocks Identification

The Anchor bolts are identified by the designation: **X - SS - NN**
where:

X bolt type (e.g. K= Hilti Kwik bolt II, S= Philips Self Drilling, W= Ramset Red Head Wedge, H=Hilti Heavy Duty)
SS bolt size (Imperial or Metric, e.g. three digits 014=1/4 inch while two digits 12 = 12mm)
NN bolt serial number from 1 to 15

Tests were identified by the following abbreviation:

ST Static Tension
SS Static Shear
DT Dynamic Tension
DS Dynamic Shear

The Concrete Blocks are identified by the designation: **X - L - NN**
where:

X block type (size) (e.g. A for Small block 21 x 12 x 6 in or 533x305x152 mm (Black))
(e.g. B for large block 21 x 16 x 12 in or 533x410x305 mm (Red))
L pouring lot number (corresponds to date, concrete mix, strength history)
NN denotes block serial number

References

1) CSA N287.2-M91, Material Requirements for Concrete Containment Structures for CANDU Nuclear Power Plants.
2) CAN3-A23.1-94, Concrete Materials and Methods of Concrete Construction.
3) ASTM E 488, Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements.

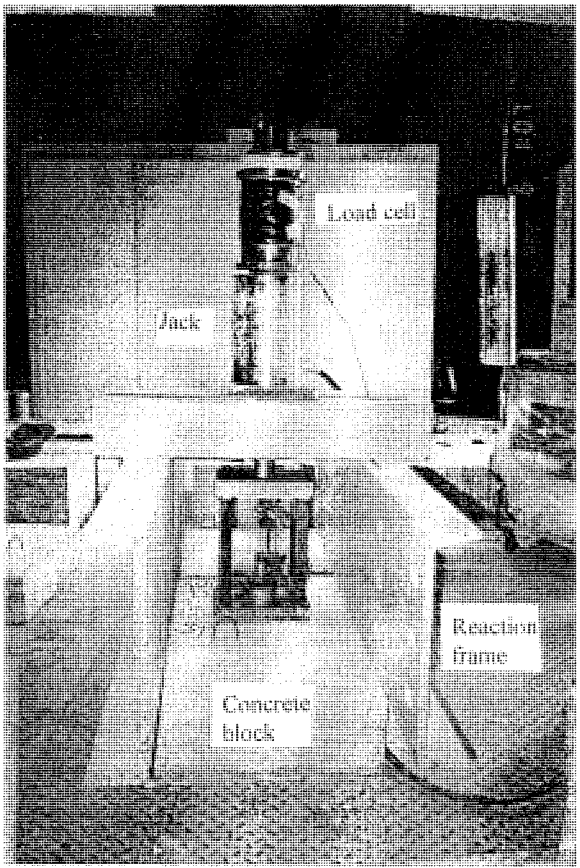

Fig 1 Static Tension Test Setup

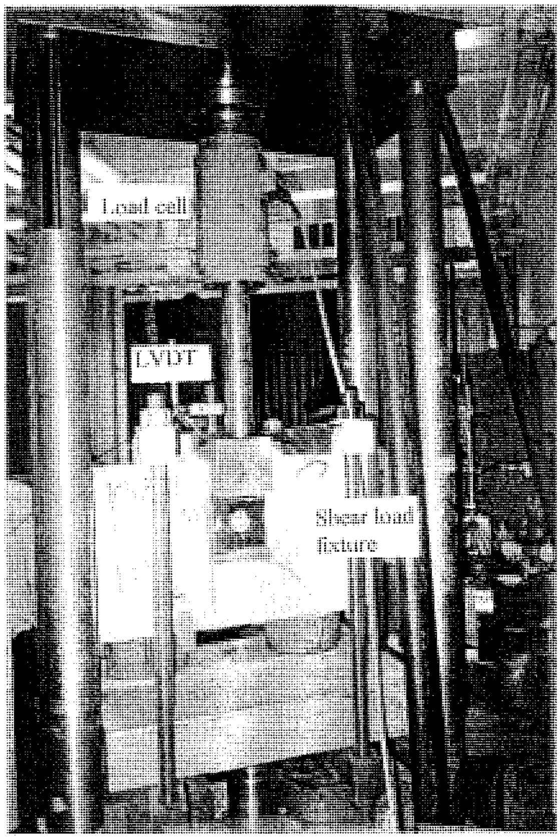

Fig 2 Dynamic Shear Test Setup

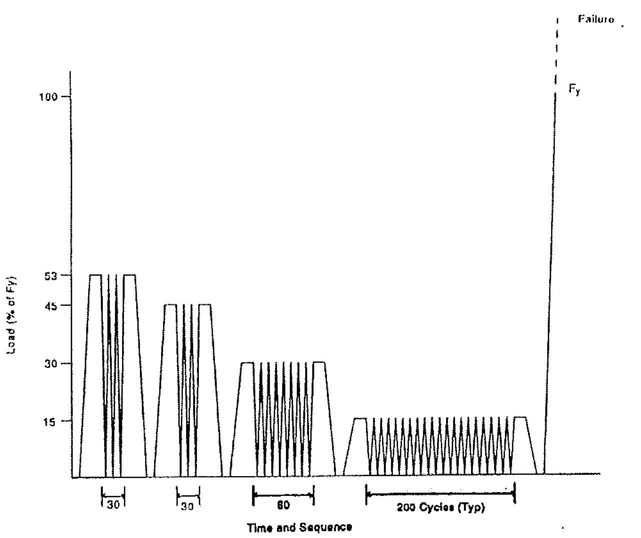

Fig 3 Cyclic Loading for Dynamic Tension Testing

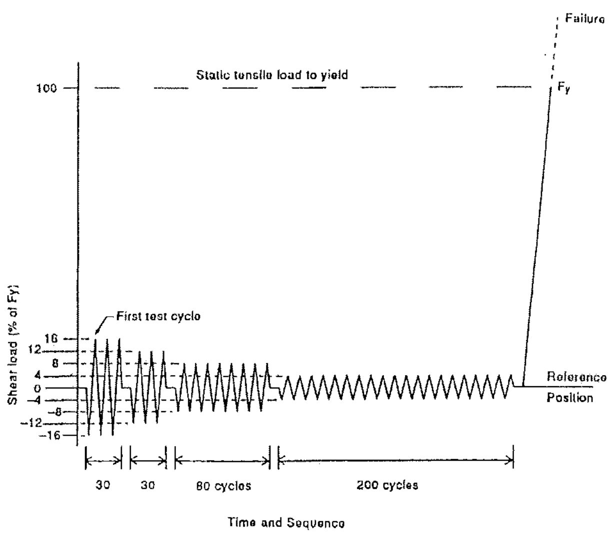

Fig 4 Cyclic Loading for Dynamic Shear Testing

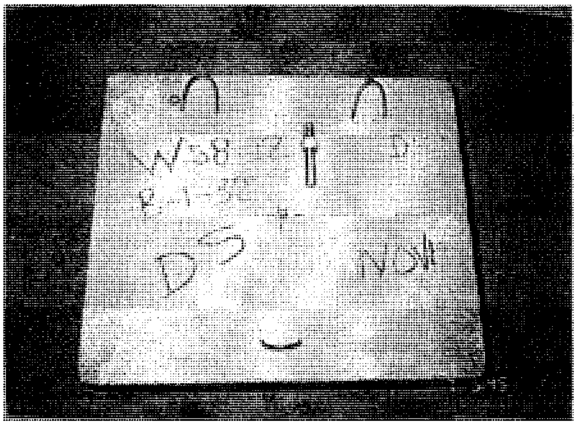

Fig. 5 Typical Failure Mode A - Bolt yield or failure

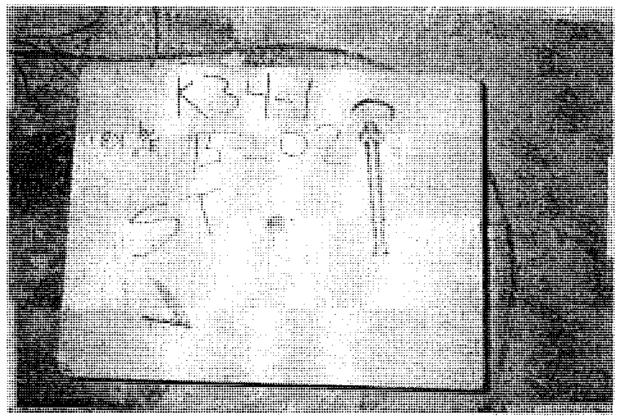

Fig. 6 Typical Failure Mode B - Anchor pull-out

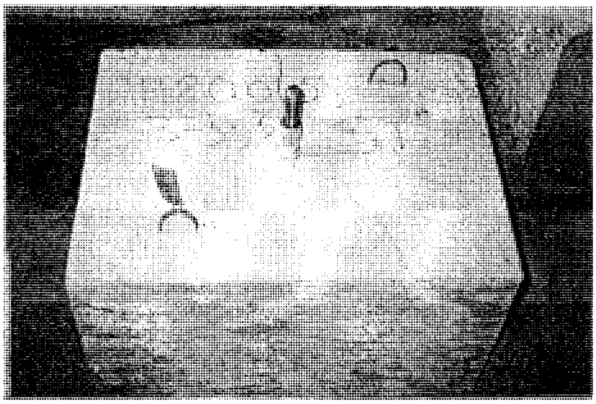

Fig. 7 Typical Failure Mode C - Anchor slip then block fracture

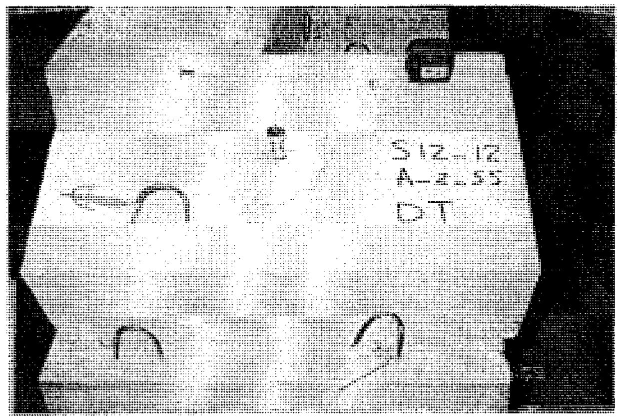

Fig. 8 Typical Failure Mode D - Cone in tension

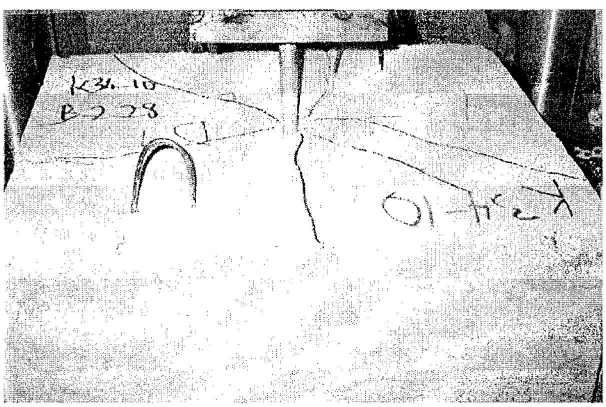

Fig. 9 Typical Failure Mode E - Radiating cracks

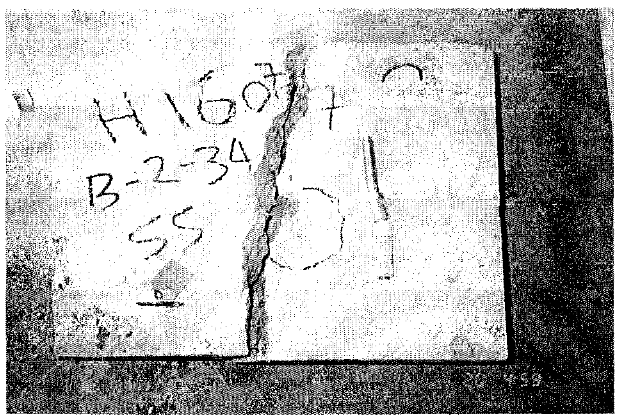

Fig. 10 Typical Failure Mode F - Bearing failure then block failure: split or wedge