5th Canadian Conf. Earthquake Engineering / Ottawa / 1987 / 5ème Conf. Canadienne Génie Sismique

Capability of unbraced cable tray support systems

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ABSTRACT: This paper summarizes the methodology and the results of an analytical and experimental program carried out for the qualification of a special category of unbraced cable tray support systems in a nuclear generating station. This group represents those cable raceways whose failure may endanger adjoining fully seismic qualified systems. Unlike the usual qualification criteria, which impose stringent stress and deformation limits, the only requirement for this group is that no structural collapse should occur during and after a Design Basis Earthquake. For this purpose, an initial test program was first developed and carried out to select optimal components, connection details, installation procedures and specific parameters required for the analysis. This stage was followed by an analytical investigation, which produced the peak seismic displacements and number of cycles to be used for the cyclic tests which were used to qualify the cable tray support systems.

1 INTRODUCTION

In nuclear generating stations, safety related electrical cable systems which are designed to remain functional during and after a seismic event to ensure continuing control for a safe shutdown of the reactor, have to be seismically qualified to Design Basis Earthquake (DBE). In order tc satisfy specified stress and deformation requirements, bracings are provided in both longitudinal and transverse directions.

In addition to the above braced or seismic cable systems, there are other cable tray systems throughout the nuclear power station which are not required to be seismically qualified. Hence, these cable tray support systems are not braced and are similar to those used in conventional (thermal and hydraulic) power stations.

However, there are certain areas in the nuclear station where the routes of the unbraced cable tray systems are located in the vicinity of seismically qualified systems and equipment. As a result, this category of unbraced cable tray systems needs to be addressed with respect to their structural integrity during a seismic event, to ensure that these systems would not collapse onto adjacent seismically qualified systems or equipment underneath. In this case, stresses beyond elastic limits and plastic deformations would be acceptable providing failure does not occur.

This paper summarizes a recent program (Ko (1986) and Naeem (1986)) carried out for the qualification of unbraced cable systems which fall into the previously described category, by means of a combination of analysis and testing.

2 DESCRIPTION OF UNBRACED SUPPORT SYSTEM

The common type of unbraced cable tray support system composes of hanger frames of variable height and number of tiers spaced at intervals up to two metres. Figure 1 illustrates the configuration of a typical frame of "trapeze" hangers. It consists of the following components:

(a) supplementary steel member which provides support to trapeze hangers;
(b) brackets which attach vertical hanger struts to supplementary steel;
(c) vertical trapeze hanger struts which carry all cable tray loads;
(d) horizontal brackets on which cable

trays are mounted; and

(e) cable trays which support the electrical cables.

The supplementary steel members are connected to the main floor structures. In "fully" seismically qualified systems, steel beams are called for, while in conventional, non-qualified systems, cold-formed double-channel 82.6 mm deep steel struts are used instead. In view of the considerable cost savings in material and installation time, various sizes of cold-formed double channel struts have been considered for the unbraced systems.

Standard brackets for attaching hangers to supplementary steel are 4 bolt L-shaped bracket (B1), 4 bolt gusseted bracket (B2) and the equal legged gusseted bracket (B3). They are shown in Figure 2. The U-shaped bracket (Figure 3, type H3000) currently used in seismically qualified systems has also been considered for the heavier 6- and 7-tier cable tray systems.

Double channel struts (82.6 x 41.3 mm in size) are currently used as hangers for all cable tray support systems. Their features of ease in installation and adjustability to local restraints make them a suitable choice as hangers in cable tray support systems.

Horizontal cable tray support brackets are specially prefabricated. They consist of a single channel strut with single-bolt plate connector at each end. The maximum width of cable tray it supports is 600 mm.

3 SEISMIC QUALIFICATION APPROACH

Qualification of a structural system is the procedure for establishing its structural integrity during and after the occurrence of a postulated event, as required by regulatory agencies and applicable standards. There are three basic methods of qualification: by analysis, by testing and by a combination of analysis and testing.

Qualification by analysis is generally done by using an appropriate analytical model of the system to be qualified. Once the model is developed, an analytical solution will be carried out in order to estimate the system's response to a specified excitation. Structural integrity can be investigated in this manner by using deformation and stress considerations at the most critical locations in the system. If testing is required in addition to analysis, results from analysis can be extremely useful in planning a test program, such as the development of test environment and test parameters. In this respect, a combination of analysis and testing is generally the most desirable method of seismic qualification. This approach has been adopted for the qualification of unbraced cable tray support systems. By idealizing the support systems with analytical models, critical testing parameters such as the axial hanger forces and the corresponding lateral hanger displacements can be established. Low cycle fatigue tests would then be performed to ensure that all components of the support systems would survive the postulated seismic event for the generation station.

3.1 Qualification Criteria

The basic qualification criterion for the unbraced cable tray support system is that no structural collapse of the system would occur during and after a Design Basis Earthquake. Stresses beyond elastic limit and plastic deformations are acceptable.

The rated cable tray loading is 102 kg/m. However, considering the load diversity for multi-tiered system and the actual plant layout, the actual cable loads can be reduced. Following a subsequent study, it was decided to select 102 kg/m for the first two trays and 75 kg/m for the remaining trays. These revised loads have been used in calculating the axial forces to be applied on the trapeze hangers in the test program.

Canadian Testing Standard for seismic qualification of equipment and systems, CSA Standards CAN3-N289.4-M86(1985), requires the structural system and all its components to be qualified to survive one DBE event. Testing procedures, according to the Standard and work by Duff and Heidebrecht (1979), should produce the same cumulative damage effects as 15 seconds of strong seismic ground motion. A rigorous approach would then require to calculate the dynamic response of the system for a large number of seismic inputs and assess which will cause the most severe damage. Apart from its impracticability, there is no guarantee that this method will identify the critical deformations. Alternatively, a series of deformation cycles at peak amplitude can be determined such as to cause the same damage. For floor mounted equipment or systems according to CSA Standards CAN3-N289.3 (1981), the minimum number of cycles for fatigue analysis shall be 25 cycles, to be applied at the maximum combined modal response level, without regard to frequency. Recent investigation for seismic qualification of concrete expansion anchors by Tang and Deans (1983) recommended a combination of test cycles with different acceleration amplitudes. Only 30 cycles are to be carried out at 100 percent peak amplitude, followed by additional tests with 25 to 75 percent of the peak value.

A more realistic approach is to include in the assessment of the number of cycles the actual parameters of the system to be qualified. The natural frequencies of the unbraced systems range from 0.4 to 4.0 cycles per second. With 15 seconds of strong seismic motion in mind, the number of test cycles can then be chosen within the range from 6 to 60. Obviously, not all will be at peak amplitude. However, since all cyclic tests for hanger systems are planned to be carried out with 100 percent peak amplitudes of displacement, the highest number of cycles, i.e., 60 is excessive. Furthermore, since the five to seven-tier systems, which support higher cable loads, are in the lower frequency range (0.4 to 2.5 Hertz), the number of test cycles would be between 6 to 38. That would be compatible with the recommendations of 25 cycles by the Canadian Standards. Taking all these considerations into account, the actual number of test cycles was conservatively determined to be 50. It is reasonable to believe that this number of test cycles, with also conservatively predicted peak displacement amplitudes, will ensure the seismic qualification of the unbraced cable tray support systems.

3.2 Analytical Approach

During a strong ground motion event, a typical unbraced hanger system will behave as a very flexible structure. This is due to both the slenderness of the structural components and the particular type of connecting brackets generally used. The actual dynamic response will be elasto-plastic and will reflect the partial rigidity of some connections and frictional slip effects. Two simple structural idealizations may be used: pendulum and cantilever models.

Pendulum Model

If hanger connections to the supplementary steel members are assumed pinned, the hangers will basically behave like pendulums. This assumption would be reasonable if plastic hinges were to develop close to the supports and offer little resistance to rotation. With cable masses lumped at their centre of mass, and depending on the number of cable trays and the lengths of the trapeze hangers, the lengths of the idealized pendulums will range from 1.1 metre (for single tray) to 3.0 metres (7 tiers of trays). The corresponding natural frequencies of these pendulums fall between 0.35 to 0.50 cycle per second. Since the main structures, where unbraced cable tray systems are to be attached, have considerably higher natural frequencies, the Ground Response Spectra may then be used to estimate the response displacements of these systems. Vertical frequencies are, however, much higher than 33 cycles per second, indicating that these systems would experience no amplification with respect to the vertical seismic excitation.

Cantilever Model

Because of the "pinned connection" assumption, the pendulum model ensures the most conservative value for the peak displacement evaluation. If the connections to the supplementary steel members are assumed to be fixed, the hangers will behave like vertical cantilevers. The assumption would be reasonable if the peak response is primarily elastic. Using the lumped mass approach previously described, the natural frequencies for both lateral and vertical vibrations are calculated. Lateral frequencies are found to be in the range of 1 to 4 cycles per second.

In the design of nuclear stations, response spectra calculated for damping values between 1 percent and 5 percent, are generally available for all main structures. As unbraced hanger systems are present throughout the generating station, an examination of all relevant floor response spectra (FRS) was required to determine the "worst" seismic loads input. For the frequency range under consideration, the unbraced hanger systems attached to floors of structural steel construction experience the most severe seismic excitation.

Subsequently, equivalent static loads using "g" values obtained from the "worst" FRS are applied onto the idealized models. For a typical Eastern Ontario site, the most severe vertical seismic force is found to be 0.8 g, while the lateral excitation ranges from 0.4 g to 2.1 g, depending on the system frequency. Since the peak elastic response capacity of the hangers was calculated to be only between 0.2 g and 0.7 g, the seismic response would therefore generally be in the plastic range. This would make the "elastic cantilever" assumption invalid. However, the peak plastic deformations may still be evaluated by using an approximate method based on an energy equivalence criterion. The basic assumption is that under the same excitation, two systems having the same mass and stiffness will absorb the same energy even if one responds elastically and the other elasto-plastically.

The displacements obtained from the above approaches are at the centre of mass. For comparison purposes and testing facilities restrictions, all displacements have been scaled for one metre long pendulum specimens, such that the actual rotations are preserved. From these valves, test parameters, as shown in Table I, were chosen for the cyclic test program.

3.3 Test Program

With the values of hanger displacements and axial forces predicted by the analytical approaches as described in the previous section, a testing program was set up and a total of 44 tests were carried out. The test set-up is shown in Figure 4. The static load was applied to the hanger test assembly by means of concrete masses. For the first cycle in all the tests performed, the applied force and lateral deflection were measured at 5 mm increments of displacement, using dynamometer and precision dial indicators. For subsequent test cycles, hydraulic pistons were used to deflect the test assembly back and forth to the required displacement.

Preliminary Tests

In the preliminary phase of testing, the main objective was to determine the most appropriate test arrangement for subsequent cyclic tests, with emphasis on the supplementary steel member and its end connections, and the bracket arrangement for attaching the hangers to the supplementary steel. For this phase of testing, an upperbound value of lateral displacement was used, based on an idealized pendulum model. A displacement of 95 mm at one metre length of trapeze hanger was used in both lateral directions. The effect of this displacement was believed to be most severe on the connection brackets. The 165 mm (6-1/2 inches) deep double channel struts were used throughout the tests as supplementary steel members and the hanger connection bracket chosen was one L-shaped and one gusseted angle bracket combination.

Cyclic Tests

Aided by the results from the preliminary tests and the parameters estimated analytically, the complete cyclic test program was then set up. Test parameters are shown in Table I. The axial gravity loads, as indicated for a pair of hangers are the sum of operating load, cable weight essentially, and the most severe vertical seismic induced force. By applying a number of cycles with the most severe lateral displacements, the hangers, the support system and its components would then be subjected to the maximum combined effect of gravity and seismic forces.

Test specification for hanger systems was prepared and two configurations were tested. For 6 and 7-tier systems, 165 mm double channel strut was used as supplementary steel and the U-shaped steel brackets were used to connect hangers to supplementary steel. The axial load on the pair of hangers was 2090 kg and the maximum lateral displacement applied was 65 mm. For systems with up to five trays, two sizes of supplementary struts (82.6 and 123.8 mm) were tested. Hanger connecting bracket to the supplementary steel would be one L-shaped and one gusseted angle brackets. The axial load used was 1545 kg and the maximum displacement applied was 70 mm. Tests were also performed with equal leg gusseted angle bracket, to be used as an alternative to avoid orientation problems that might arise in the process of installation at site.

Tests on the horizontal cable tray support brackets completed the cyclic test program. An axial load of 368 kg was applied onto each support bracket, producing the combined effect of operating and seismic loads. Unlike the previous set-up, two sets of hangers had to be installed for each test, including also cable trays supported in place by the horizontal brackets. This would simulate the effect of the stiffness of the cable trays on the support brackets when the support system undergoes 75 mm displacement in the transverse direction.

4 RESULTS AND OBSERVATIONS

4.1 Preliminary Tests

Important observations were made from preliminary tests. It was found that the double channel struts performed well in all the tests, indicating the feasibility of substituting the supplementary steel beams with channel struts as supporting members. The angle bracket arrangement for hanger connection to supplementary steel did not perform satisfactorily for 7-tier cable tray hangers. Severe damages to the vertical hangers (vertical cracking in flanges of channels, see Figure 5) occurred at the lower bolt location in the first cycle of loading test. As a result, the stronger U-shaped steel bracket specially designed for systems were used in all subsequent tests for 6 and 7-tier systems. The angle bracket arrangement, however, performed satisfactorily for cable systems up to 5 tiers. The orientation of the angles was found to have significant effects on the test outcome; only the configuration with the long leg of angles installed vertically survived the cyclic test. This observation was confirmed in later tests.

4.2 Cyclic Tests

Based on the cyclic tests performed the following observations were made.

Supplementary Steel Members

The 165 mm deep double channel struts performed well as supplementary steel members for 6 and 7-tier unbraced cable tray support systems, while 123.8 mm channel struts were found to have adequate capacity for systems up to five trays. Tests with 82.6 mm struts as supplementary steel showed severe cracking in the lower channel flanges where trapeze hangers were attached. Cracks first occurred in the supplementary strut at both hanger connection locations and these cracks then propagated towards each other to form one large crack above the hanger during the cyclic test (Figure 6). At the same time, slippage of the hanger up to 20 mm had also occurred. These characteristics were considered to be undesirable and hence the 82.3 mm double channel strut was not recommended to be used in unbraced systems.

The effects of the connection details of the supplementary struts to the steel beams were investigated. The struts were welded either to the web or to the bottom flange of the main structure steel beams. No significant difference in performance of the hanger system could be observed.

Vertical Hanger Struts

The double channel struts, 82.6 mm x 41.3 mm, were found to behave quite adequately in the tests and did not present any problems from the seismic qualification point of view.

Type H3000 Steel Brackets

The U-shaped (Type H3000) steel brackets, connecting the trapeze hangers to the supplementary struts performed very well in the fatigue tests under 7-tier cable loading. No visible cracks or damages were observed either in the supplementary struts, the trapeze hangers or the brackets themselves.

Unequal Leg Angle Brackets

Pairs of angle brackets, types B1 and B2 were tested for 5-tier cable loading. Results confirmed findings from preliminary tests. Angle brackets installed with short leg vertical failed in all the cyclic tests. After the initial four to five cycles, severe damages occurred to both flanges of the hangers. Major portion of the hanger loads appeared to be carried by the inner L-shaped angle brackets and their connecting bolts were bent. Slippage of hangers, up to 25 mm, had also occurred. Further tests were considered to be unsafe and hence were terminated after only five cycles. On the other hand, similar angle brackets B1 and B2, installed with the long leg vertically performed much better in the cyclic tests. Cracks formed in the vertical hangers during the initial cycles, but the cracks stabilized in subsequent load cycles and the full scope of tests was completed without collapse.

Equal Leg Angle Bracket

Equal leg gusseted angle bracket (Type B3), paired with the L-shaped bracket (B1) were also tested. All samples behaved in a similar pattern and survived and 50 test cycles.

Horizontal Support Brackets

Initial cyclic tests on horizontal cable tray support brackets showed that when the bracket was connected close to the end of the hanger (top of bracket was 85 mm from the end of the hanger), the connecting bolt actually slipped out of the hanger after two test cycles and the applied load fell down. Subsequent cyclic tests were carried out with the end distance adjusted to 170 mm. The brackets survived the full 50 test cycles under peak lateral displacements of 75 mm.

5 CONCLUSIONS

Based on the results from the analytical and cyclic test program, the unbraced cable tray support systems can be considered to be qualified with respect to the functional requirement of "no collapse" under the postulated DBE event if the following requirements are met:

(a) Rolled steel beams were designed to be used as supplementary steel members. They were tested and results confirmed their acceptability.

Double channel struts were also tested and results indicated that they could be used in place of rolled steel beams as supplementary steel members.

The following sections are qualified: 165 mm deep struts for 6 and 7-tier systems and 123.8 mm deep struts for systems with up to 5-tiers of trays.

(b) The vertical trapeze hangers, as tested, i.e., 82.6 mm x 41.3 mm, were found to be adequate and are, therefore, qualified.

(c) Connecting brackets for trapeze hangers to supplementary steel members play a significant role in the behaviour of the unbraced hanger systems. U-shaped (Type H3000) brackets are qualified for use for 6 and 7-tier systems, while a combination of L-shaped and gusseted angle brackets (Type B2 and either B1 or B3), with long leg of angles installed vertically, is required for systems up to five trays, and

(d) Horizontal cable tray support brackets, in the form of a single channel with welded plate connectors at each end, have adequate capacity for the rated cable load of 102 kg/metre. End distance for installation of the lowest support bracket in the system is required to be not less than 170 mm.

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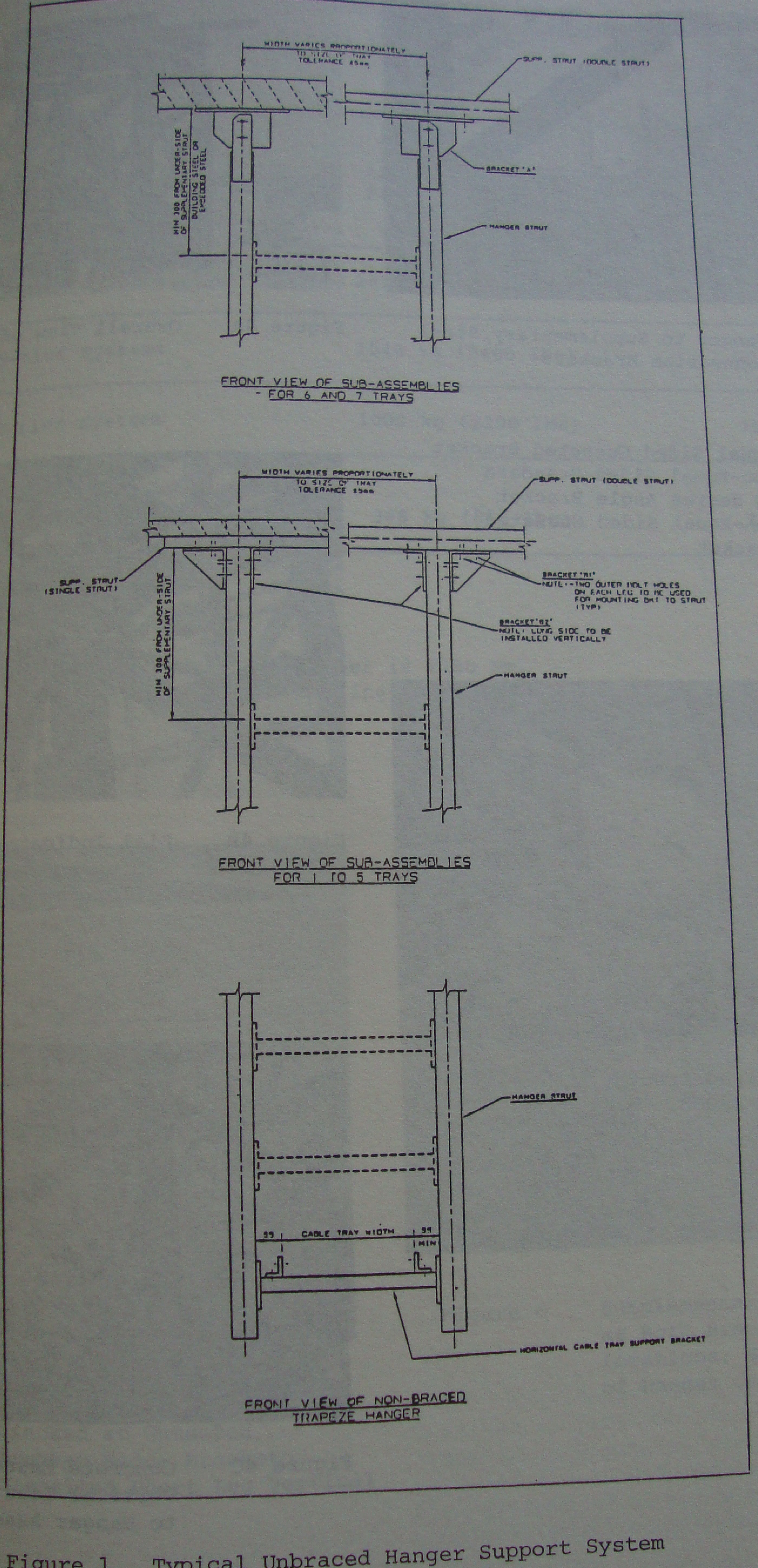

Figure 1   Typical Unbraced Hanger Support System

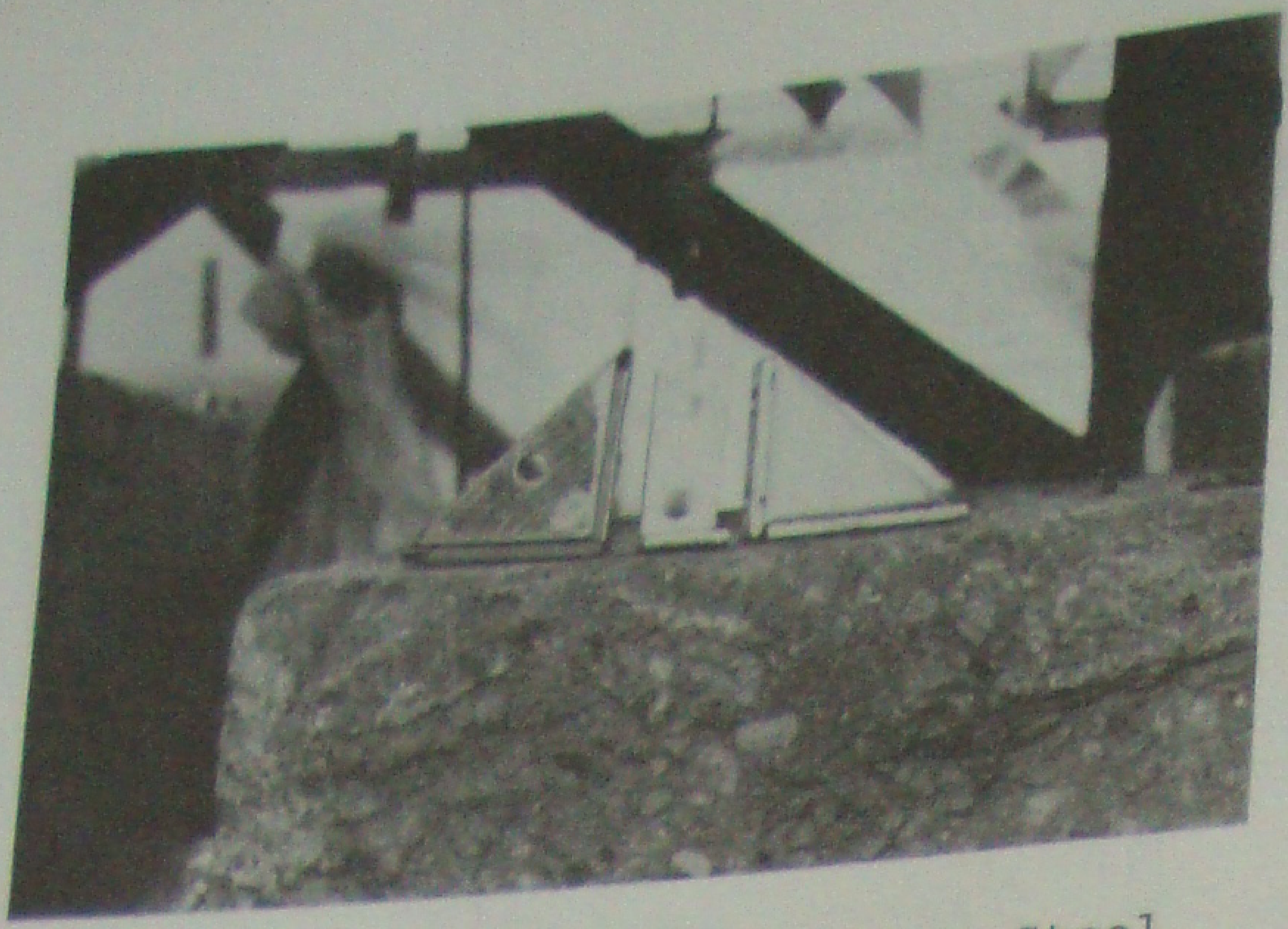

Figure 2 Hanger to Supplementary Steel Connection Brackets

From left:

Type B3 Equal Sided Gusseted Bracket
B2 Non-Equal Sided Standard 90 degree Angle Bracket
B3 Non-Equal Sided Gusseted Bracket

Figure 4A Overall View of Test Set-Up

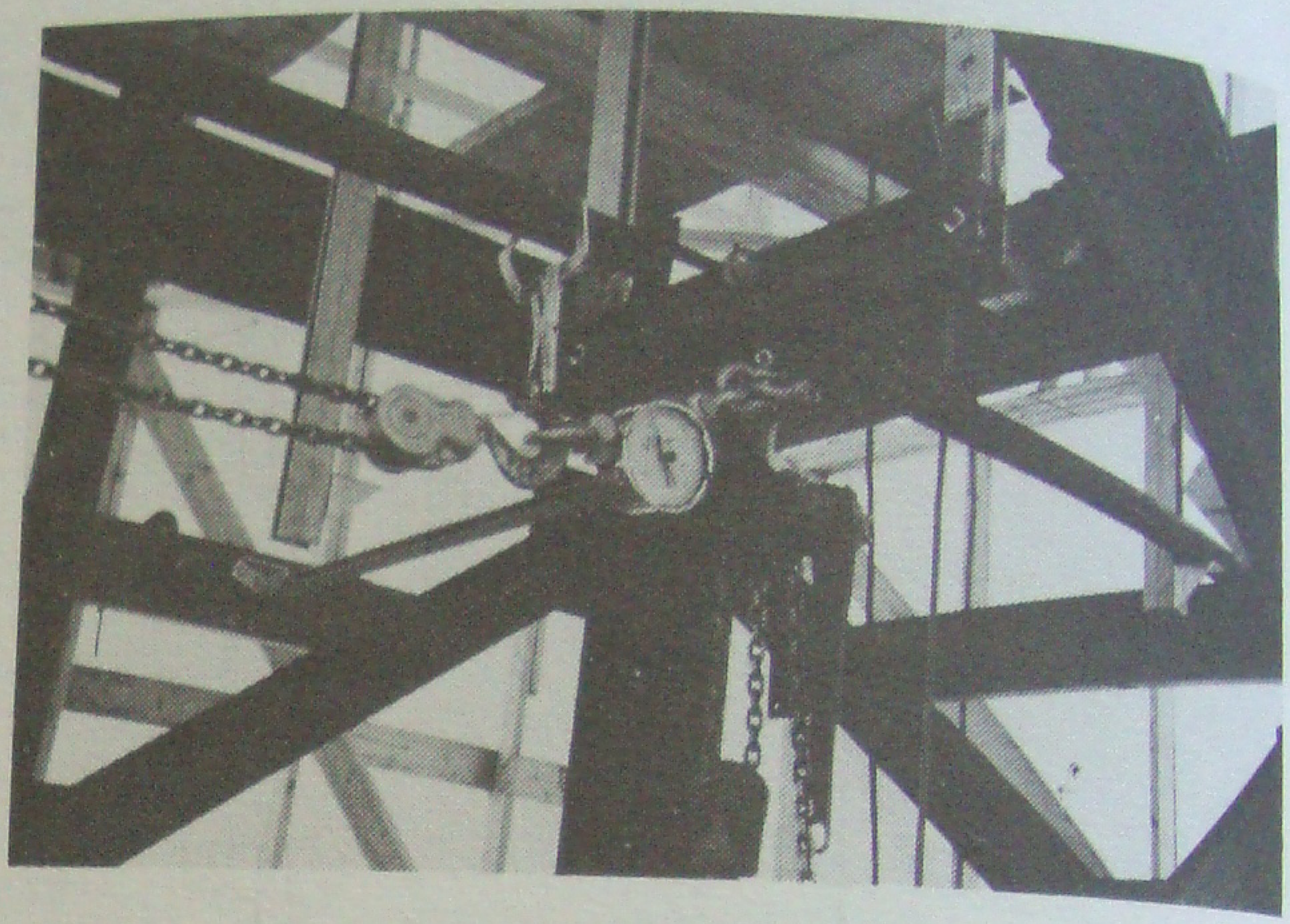

Figure 4B Dial Indicator and Dyamometer Set up to Measure Lateral Deflection and Applied Force

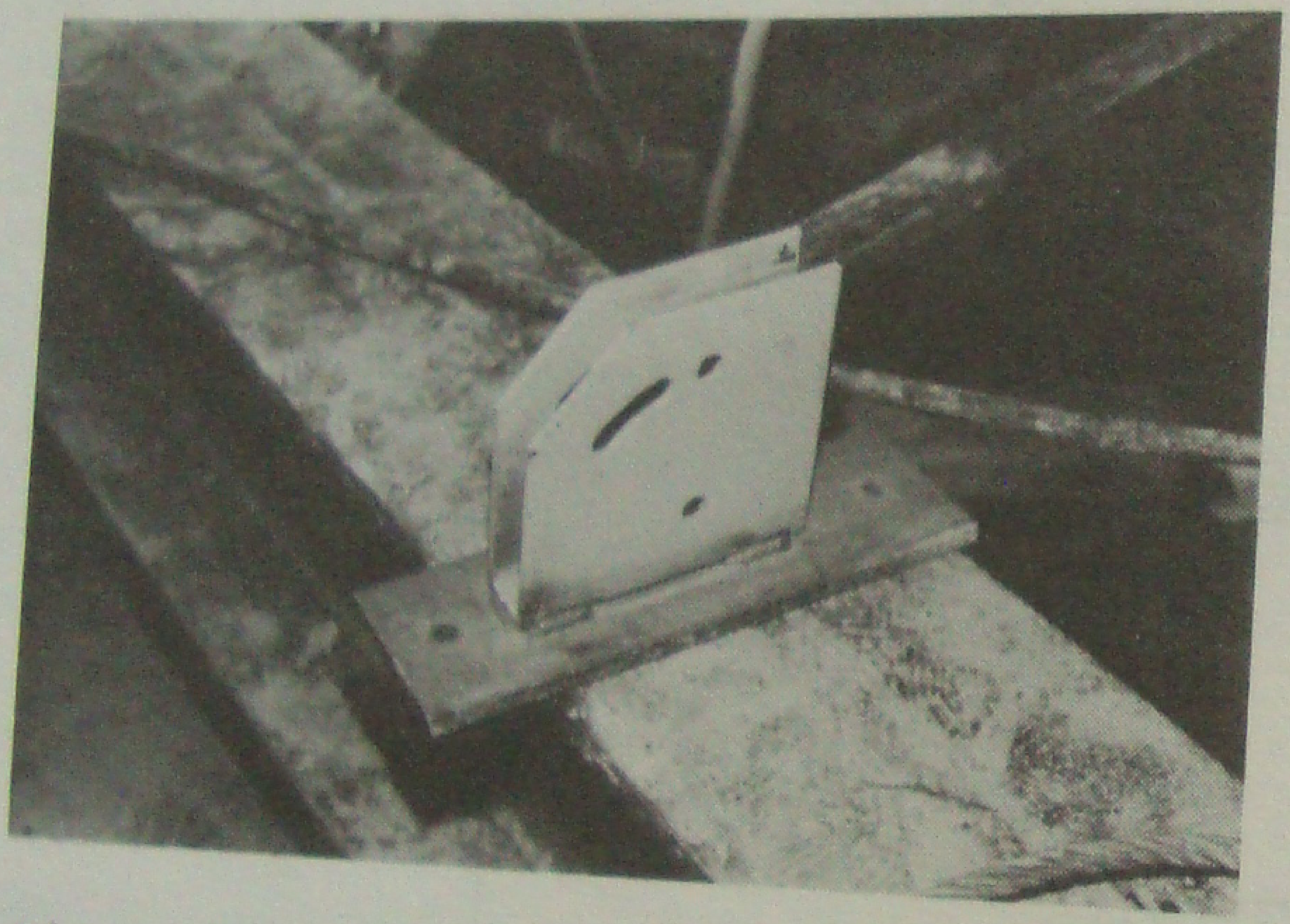

Figure 3 U-shaped Bracket Type H3000

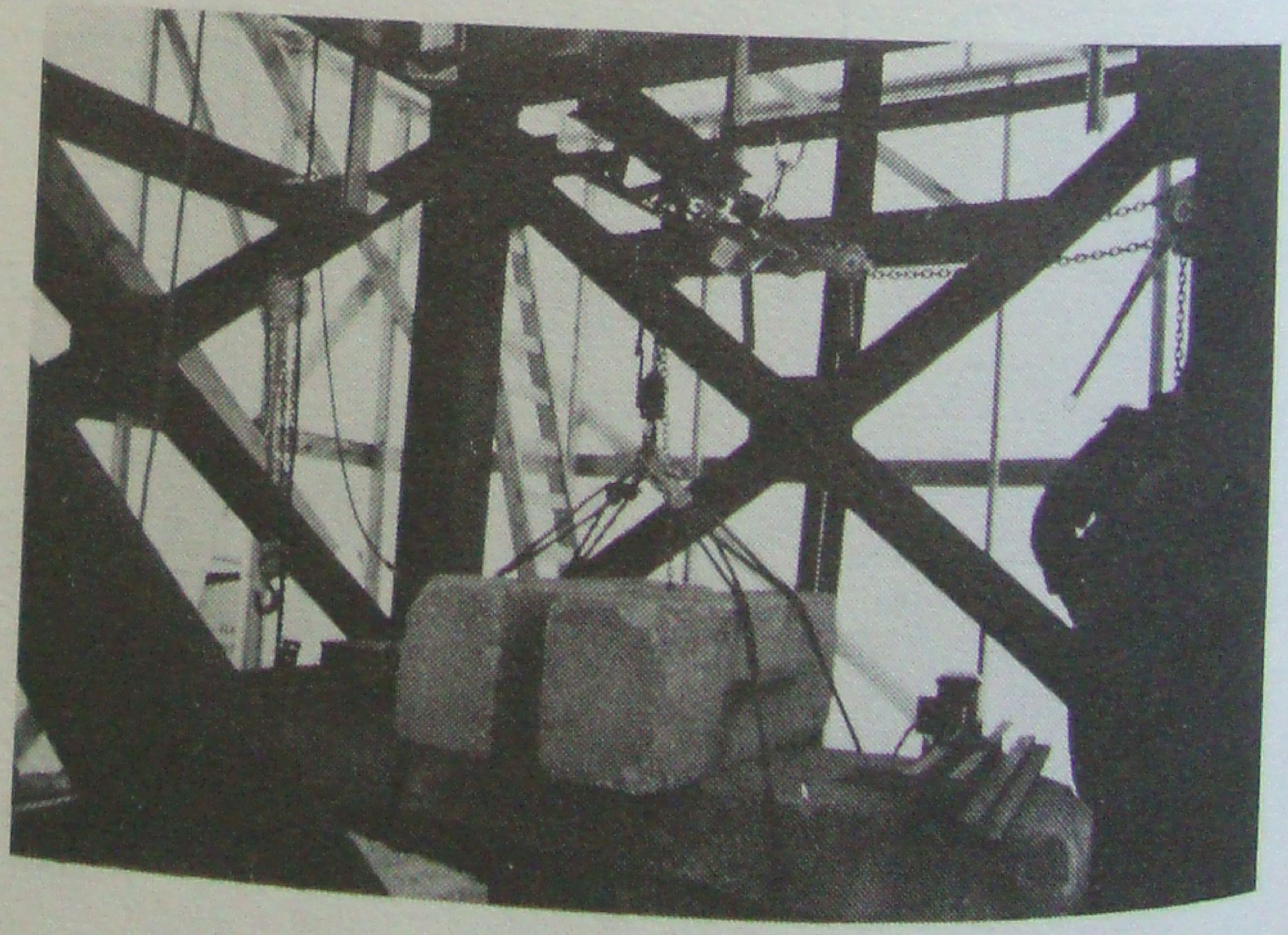

Figure 4C Concrete Masses as Vertical Load Applied to Hanger Assembly

TABLE I

Cyclic Test Parameters

Unbraced Cable Tray Support System	Axial Load on a Pair of Trapeze Hangers	Max Lateral Displacement at 1 metre length of hanger from top support (mm)
6 and 7-tier Systems	2090 kg (4600 lbs)	65
4 and 5-tier Systems	1545 kg (3400 lbs)	70
up to 3-tier Systems	1000 kg (2200 lbs)	75
Single Tray System, Test for Horizontal Supp Bracket	368 kg (810 lbs)	75

Note:

- Span of supplementary steel member is 2150 mm.
- Maximum number of cycles of testing is 50.

Figure 5 Vertical Hanger Strut Cracked at Gusseted Bracket Side; Brackets Installed Short Leg Vertical

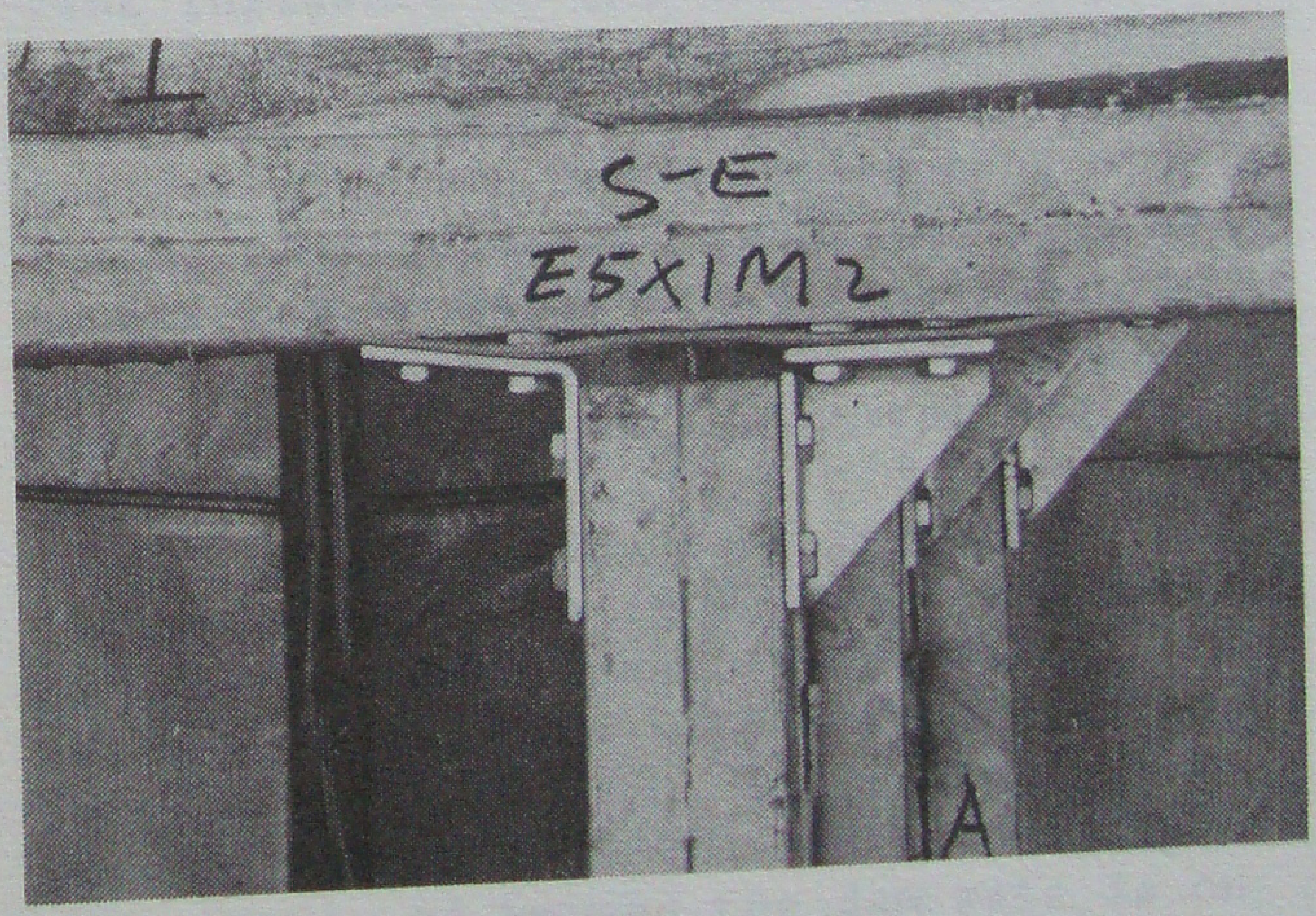

Figure 6 Supplementary Strut Cracked at Both Bracket Connection Locations; Severe Slippage of Hanger Occurred