Strain measurements on the temporary road deck for the Toronto Subway

Schriever, W. R.

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NATIONAL RESEARCH COUNCIL
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DIVISION OF BUILDING RESEARCH

STRAIN MEASUREMENTS ON THE TEMPORARY ROAD DECK FOR THE TORONTO SUBWAY

BY

W. R. SCHRIEVER

PREPARED IN CO-OPERATION WITH THE TORONTO TRANSPORTATION COMMISSION AND NOW CIRCULATED FOR COMMENT

OTTAWA

SEPTEMBER 1952

DBR REPORT
R 9

THE GENERAL PLAN OF YONGE STREET ROUTE SHOWING THE ALIGNMENT AND GRADES. MAXIMUM GRADIENT WILL BE 3·5%

T.B.R. REPORT R 4

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Research Report No. 9
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Ottawa
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PREFACE

The Toronto Transportation Commission is constructing Canada's first subway. This great construction project cuts through the heart of downtown Toronto. It is thus beyond question one of the most complex building operations yet to be carried out in the Dominion. Completion is anticipated by the end of 1953.

The Division of Building Research, N.R.C., has been privileged to be closely associated with this unusual project since the start of its work, following the writer's personal connection as a consultant to the T.T.C. on soil and foundation problems until he came to Ottawa in 1947 to assume his present position. When construction of the subway started (in 1949) the Commission kindly agreed that the Division, in effect, might use the job as a large scale "building research laboratory" in return for such special assistance as it might render with unusual problems encountered as construction proceeded.

Accordingly, the author of this Report (Mr. W.R. Schriever, an Assistant Research Officer in the Soil Mechanics Section of D.B.R.) moved to Toronto in September, 1949, and was engaged for the next two years as Research Engineer on the subway project. He continued to be a member of the D.B.R. staff but acted generally as though he were on the T.T.C. construction engineering staff. The arrangement worked admirably, it is believed to mutual benefit.

Many problems were investigated and some major projects undertaken. This is the first of a number of reports which will record the results of these investigations. This paper deals with a study of the actual loads to which the temporary road deck structure was subjected and the corresponding actual stresses set up in the steel. It is thus a contribution to the rather limited literature dealing with the true loading of civil engineering structures, a field of work in which the Division hopes to make further studies. The need for research work of this kind has only recently received renewed attention as, for example, in a notable paper by Prof. A. G. Pugsley*. The practical implications of its conclusions will be obvious.

The paper is issued first in this form by agreement with the Toronto Transportation Commission. It is hoped that the author may be favoured with critical comments from those who

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* Pugsley, A.G. "Concepts of Safety in Structural Engineering" Journal of the Institution of Civil Engineers, London, March 1951.

read the paper in this form. If it seems to be agreed by those competent to judge that the paper should be published, the permission of the Commission will be sought for submitting a revised version of this paper to one of the major civil engineering societies for publication and public discussion.

Ottawa
September, 1952.

Robert F. Legget,
Director.

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SYNOPSIS

This report deals with strain measurements made on the deck beams and some other parts of the temporary steel structures of the street deck used during the construction of the Yonge St. Subway by the cut-and-cover method. The results of measurements on the various deck beams are presented. The investigation included both normal traffic loads as heavy load combinations, and to some extent, earth pressure. The maximum values of stresses and the frequency of occurrence of loads are discussed, with a view to improving future design basis.

STRAIN MEASUREMENTS ON THE TEMPORARY ROAD DECK FOR THE TORONTO SUBWAY

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W. R. Schriever

Canada's first subway has been under construction in Toronto since 1948. This project, undertaken by the Toronto Transportation Commission, provided good opportunities for study of soil and foundation conditions and of some related design and construction problems. A number of investigations were therefore undertaken jointly between the Division of Building Research of the National Research Council and the Toronto Transportation Commission.

Many problems encountered in the course of the design and construction of a subway structure still leave much room for improvement in their solution. Research on some of these questions could therefore contribute to more economical construction. It is hoped that this research may be of interest and value to the construction industry.

Numerous subjects worthy of investigation were encountered during the design stages of the project and demands for research projects were plentiful. By the time construction began, the number of projects had been reduced to the following:

1. Recording of a complete engineering and geological soil profile along the excavation including groundwater observations;

2. The measurement of strains occurring in various steel and timber elements of the shoring of the subway excavation and of the temporary road deck in order to determine horizontal and vertical loads;

3. The measurement of stresses occurring in some parts of the permanent reinforced concrete structure;

4. The dissipation of ground vibrations due to construction operations;

5. The recording of soil temperatures beneath the subway; and

6. Observation and study of some construction problems such as compaction methods, drainage, and underpinning.

Due to the limited staff available both from the Toronto Transportation Commission and the National Research Council, it was necessary to concentrate efforts on one or two of the investigations mentioned above, as all of them required extensive preparations and a great number of routine measurements over many months.

This report deals with the measurement of strains occurring in various steel elements of the temporary road deck. This deck is an important part of the construction method known as "cut-and-cover", which is described in more detail in the next section. The temporary road deck, which carries all traffic including street cars during construction of the subway structure underneath, represents a major item of cost, a very large amount of steel being required for it.

The deck members were designed to carry a very heavy combination of loads consisting of crane cars, street-cars and trucks. In view of this assumed load concentration and the question of the probability of the actual simultaneous occurrence of such heavy loads, it was thought that an experimental study of actual strains in the steel decking would be justified. Although the part of the problem dealing with static loading (earth pressure and dead load) was also studied, the major part of the study was concentrated on the transient stresses resulting from live loads considered from their two separate aspects: (a) magnitude, and (b) frequency of occurrence.

2. THE TORONTO SUBWAY

(a) A General Note

The first line of the proposed Rapid Transit System for Toronto, which is under construction at the present time, is the Yonge Street Line, now often referred to simply as the Toronto Subway. Of the total length of 4.6 miles, roughly one third is being constructed under heavily travelled streets in the heart of the city, mainly under Yonge and Front Streets, by the cut-and-cover method of construction. This construction method, by which the subway is built from the ground surface, was imperative, because the subway was designed to be as shallow as possible in order to facilitate the passenger transfer to and from surface transportation and because of the local geological formation. During construction all normal traffic, including street-cars, is carried on a temporary road deck, while the major part of the excavation and the construction of the reinforced concrete subway structure proceeds underneath.

Support of the sides of the cut against earth pressure and support for the loads on the deck is achieved by steel H piles known as soldier piles, which are driven into the ground along both sides of the street, at 6 to 8 foot intervals. The first part of the excavation is then carried out, to take care of the great number of utilities and to install the road deck. Normal street traffic can be resumed on the road deck, while construction work continues underneath. Wooden lagging is inserted between the soldier piles as the excavation is deepened until it reaches final grade, which is some 30 to 40 feet below the street surface. The actual subway structure consisting of a reinforced concrete "box" is then constructed, sand backfill placed on top and the street repaved after removal of the deck.

The remaining two thirds of the subway consist partly of cut-and-cover sections not under city streets but on a private right of way, some distance off Yonge Street, and partly of open cut, with cross streets carried on overhead bridges.

(b) Description of the Temporary Road Deck

Various types of road deck constructions are used on this project, depending on the required span, the available clearance underground and also on the steel sections available at the time, which was a period of steel shortages. For the box sections of the subway (i.e. between stations) intermediate sections (transitions, etc.) and some of the narrower stations, 36-inch wide flange beams of various weights are used; for station sections either trusses or 36-inch beams with knee braces or posts as a means of reducing the unsupported span. Typical deck constructions of the three main classes are shown in Figs. 1 and 2. Trusses, used extensively in the first station sections at Queen Street and at Union Station, were not used as much later on mainly because, although lighter in weight, they involve much more labour for placing and welding and are not as adaptable in re-use. Attention in the measurements was therefore concentrated on the beam type deck constructions.

(c) Construction of the Temporary Road Deck

A brief description of the construction work in the "cut-and-cover" method has already been given in a previous chapter. Construction of the road deck proper follows these lines. First, along each side of the street, soldier piles are driven into the ground (Fig. 4). The required depth of driving is 8 ft. below the final grade level in soil while in rock the piles are driven to refusal (Fig. 5). The pavement and the street-car rails are then removed and the first lift of the excavation can be taken out from the surface by a power shovel (Fig. 6). Excavation around the many utilities, however, has to be done by hand (Fig. 7). The soldier piles are all cutoff at the same depth below street surface and capped by steel beams. By means of two truck mounted cranes, the main deck beams can then be laid across the street at 12-foot intervals (Fig. 8) supported laterally by timber spreaders and tie rods and fastened to the cap beams by welded brackets. Stringer beams are next welded to the web of the main beams (Fig. 9) and 12- by 12-inch timbers laid along the outer lanes for use by the truck mounted crane. The utilities are attached to the underside of the deck by steel cables or suitable timber construction (Fig. 10). With the laying of ties, street-car rails and the remaining part of the deck timbers the temporary roadway is completed and traffic can be resumed (Fig. 11).

The live load assumption which was made in the design of the deck construction and which was approved by the City of Toronto is shown graphically in Section 4. All deck beams were designed as simple beams.

3. THE SAFETY OF THE TEMPORARY ROAD DECK

(a) The Safety of Engineering Structures in General

In using a certain allowable stress in the design of an engineering structure, the engineer usually visualizes the "factor of safety" as the ratio of the stress at failure (strength) to the allowable stress with which he is designing. Possibly he thinks of another factor of safety with regard to yield, i.e., the ratio of the stress at the beginning of inelastic yield to the maximum stress occurring in the critical points in the design of the structure. He knows that values of slightly over three and two respectively, are used at the present time for these two factors of safety for structural steel. The engineer should always consider also the question whether the above values actually represent the factors of safety of the full-scale structure and, further, what this factor should be.

In the light of the many considerations entering into the picture of safety in structural engineering, it seems appropriate to review some of its pertinent aspects. As A. G. Pugsley points out in his paper "Concepts of Safety in Structural Engineering" (1) the factor of safety was defined first, in the late eighteenth century when cast-iron began to be used as a structural material, as the ratio of the load required to break a girder to the greatest load the girder was actually required to carry. It can be seen that this factor of safety does not conform with the term in its present use, because now, as mentioned before, it is generally applied to stresses and not to loads. A large margin of safety was desirable at that time for cast-iron construction because of the many hidden faults in large castings. Thus a factor of safety of four, and six in the case of rolling loads to allow for impact, was used. Later, when the beam theory became generally known, it was possible to use the factor of safety, not with breaking and working loads, but with breaking and working stresses. Thus the "stress factor of safety" was introduced and connected directly with material testing which, in a new and unprecedented way, provided numerical values for the strength of various materials.

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(1) Journal of the Institution of Civil Engineers, London, March, 1951.

This development paralleled the arrival of wrought iron and mild steel which through their ductility revealed the importance of yield stresses. The ductility in the material introduced the possibility of large inelastic or permanent deformations without actual collapse. This greatly increased the safety of a structure as a whole, that is as long as no buckling was involved, for the stability of columns is, of course, a different matter. It is interesting to note in this connection that the stress factor of safety became so firmly embedded in engineering practice that even results of column tests and theories were and often still are discussed in terms of stresses rather than loads.

In the early days, as A. G. Pugsley remarks, most of the maximum external loads acting on bridges and buildings, apart from wind loads, were thought to be clearly definable and in most cases no question of the likelihood of their actual occurrence arose. In aeronautical engineering however, ideas of the probability or of frequency of occurrence of loads had to be introduced into considerations of margins of safety. A military aircraft, for instance, is designed with values of the forces acting on the wings which were based on past experience. If found satisfactory under reasonable conditions, an aircraft would be loaded further with fuel and armament or, be made more manoeuvrable, until some structural failures began to occur. Laboratory tests to destruction of complete wings then permitted the application of the results of this experience to other cases.

Such is not the case for large civil engineering structures where it is usually impossible to depend on tests to destruction and where external loads are frequently difficult to measure and are to a certain extent uncontrollable. Empirically limited working stresses, linked with conventional stress calculations for idealized loading cases, are therefore used in general. On the other hand, where external loads can be controlled by the designer, a new outlook on margins of safety and therefore greater overall structural economy becomes possible. As will be seen later on, in Toronto the maximum load for the temporary road deck could be controlled to a certain degree.

For no structure can the maximum load to which it will ever be subjected be forecast with absolute certainty. There is therefore always some "accident risk" involved, although this risk may be extremely small. In other words, it would be uneconomical, even impossible, to design and build a structure that is absolutely safe, as under unforeseen circumstances, as in an emergency, it is possible that a heavier load than the design load may have to be carried by the structure. The responsibility as to what extent this possibility of excessive loads, as well as to what extent deficiencies of design and workmanship, corrosion, etc., should be allowed for in the design, normally does not fall upon the designing engineer, for building codes or other regulations specify the design load and the greatest allowable stresses with which he may design permanent structures. Such specifications, however, are general rules and must necessarily be rather conservative.

On the other hand, inaccuracies of design assumptions are usually toward the safe side only. In cases where defects in material quality and workmanship are reasonably apparent and when at least part of the maximum design load can be controlled by the designer (or owner), an improvement in the economy of the design can be achieved. This, in fact should be achieved, especially in times of scarcity of materials.

(b) Statistical Approach to the Design Load Problems

There is often a regrettable tendency to regard extreme safety in a structure as a virtue in itself, without due consideration of the question whether this degree of safety is actually necessary or whether the public actually wants to be protected to this extent. Where heavy load combinations approaching or reaching the design load are likely to occur only on very rare occasions or not at all, it does not seem reasonable to consider this design load on the basis of the usual allowable stress--that is to provide the full factor of safety--especially in cases where the "load factor of safety" probably considerably exceeds the "stress factor of safety". The fact that extreme load combinations, such as the coincidence of an extreme wind with an extreme snow load on buildings, are not very likely, has been recognized in practice and is often allowed for by an increase in permissible working stresses. Another example of the improbability of coincidence of extreme loads is in the design load for skyscrapers as it is assumed that it is unlikely that on all floors the maximum floor loading will occur simultaneously.

In this same connection mention should also be made of the impact factor, which is defined as the ratio of the dynamic stress for a vehicle moving over a structure to the static stress for the same vehicle stationary on the structure. Since statistically and actually the maximum impact effect is not likely to be produced simultaneously by all parts of the heaviest live load combination, it is not usually necessary to apply the maximum impact factor to the full combined live load, except for railway bridges.

For temporary structures, such as the one in Toronto, therefore, an attempt should be made to determine the frequency or probability of occurrence of heavy load combinations. This, in a general case, would mean making a statistical study of continuous records of traffic loads passing over the structure. If continuous records of strains occurring in a main member are taken, these would indirectly represent traffic loads. They can, however, for practical reasons, be considered in terms of stresses, rather than strains or loads. If the results are plotted in form of a frequency distribution diagram a curve of the type shown in the insert in Fig. 18 would generally be obtained. In this diagram stresses corresponding to loads of the order of magnitude of the design load in most cases are at the extreme right or probably even beyond the values that can be shown by such a curve. Consequently, in all practical cases where records cannot be obtained over extremely long periods, the frequency of very heavy loads may only be obtained by extrapolation of the curve. Extrapolating from frequencies of measured loads to the frequencies of extreme loads is difficult, however, and sometimes of doubtful value. This is especially true in a case such as the one in Toronto. When certain definite loads become predominant, such as the weights of street-cars, and ready-mix concrete trucks, the shape of the frequency distribution curve varies greatly from the normal curve, which is obtained, for instance, for rain storm precipitation, wind pressures, etc. and statistical rules cannot be applied. The theory of probability, then, is no substitute for the measurements of a great number of actual loads, as no matter how much time was spent on curve fitting, the accuracy of the curve for extreme loads would be uncertain. Consequently sound judgement has to be used without much quantitative help from the law of statistics.

(c) Fatigue

As is well known, a structural member subjected to millions of repetitions of load may fail by rupture even though the stress is below the elastic limit stress. This fatigue failure is due to progressive fracture caused by the very gradual spreading of minute cracks. The number of load cycles which has to be reached before the possibility of fatigue failure has to be considered is, very roughly, one million. Since street-cars pass over each pair of stringers a sufficient number of times to cause 2,000 or more axle loads a day and as the life of the road deck is about one or two years, the stringers come within the range where the fatigue strength is a decisive factor, as far as the number of cycles is concerned. The magnitude of the stresses in the stringers, however, and even more so in the main beams, is, as will be seen later too small to indicate a danger of fatigue failure in the deck in question.

4. STRAIN MEASUREMENTS ON THE TEMPORARY ROAD DECK

(a) General Remarks

If the above general considerations are applied to the Toronto problem, their importance can readily be seen, because the design load consists of very heavy concentrations which are likely to occur simultaneouslv only on very rare occasions. The justification of the design load is therefore questioned. Frequency considerations of load alone, however, cannot apply to all parts of the temporary road deck, since there are other aspects entering into the choice of the sections, for the soldier piles and the cap beams for instance, such as driving through hard soils with boulders and the resistance of earth pressure.

In the light of these facts it was decided to carry out an investigation of strains occurring in the deck beams and some other structural elements of the temporary road deck. This work was done co-operatively by the Toronto Transportation Commission and the National Research Council. The Toronto Transportation Commission besides assisting the National Research Council personnel also made available the following:

(1) Auxiliary equipment such as the special hut for housing the equipment during the tests;

(2) The personnel of the Testing Subsection of the Rapid Transit Department when needed;

(3) The use of the Soils Laboratory and of some of the work-shop services;

(4) The use of the crane car with crew for loading of the deck beams;

(5) The use of the automobile assigned to the Testing Subsection;

(6) The co-operation of the traffic inspectors during the loading of the deck beams.

The National Research Council supplied personnel to work on this project and all scientific equipment.

The majority of strain measurements for the subway were carried out on deck beams since they are the elements of the temporary structure for which an improvement in the economy of design would be obviously most important. Tonnage of steel in the deck beams is the greatest, apart from the tonnage used for piles for which, however, stresses due to traffic loads are not the decisive factor. Only a few measurements were made on one of the trusses which are used for the wider span of the station sections of the subway. Because of the much greater amount of labour involved in the cutting, assembling, and welding, the trusses were abandoned in favour of I-beams with knee braces.

The knee braces not only serve to reduce the free span of the I-beams but also act as partial shoring of the supporting piles against earth pressure. In other words, they represent structurally one step in the transition from a frame to an arch with a corresponding reduction of bending movement. Appreciable stresses were therefore expected in the knee braces themselves, especially in view of the fairly light steel sections used for them; a number of strain measurements were made, consequently, on these braces.

The stringers represent the main longitudinal element in the deck which should be considered as a grid system for analysis. Consequently, when stresses in the deck beams were found to be low, measurements were also made on some of the stringers in an attempt to investigate the distribution of load from a loaded main beam to the neighbouring main beams.

As all deck beams, for economical reasons, have constant cross-sections, measurement in the section of the maximum stresses was considered sufficient. Strain gauges, therefore, were attached at the centre of the span, which in most cases coincided approximately with the centre line of the street and of the street-car tracks. In one case measurements were also taken at the quarter points of the span.

Stresses occurring in the deck beams consist of two parts, a static part due to dead load and earth pressure and a superimposed dynamic part due to live load (street-car and motor traffic). For the first part which, due to earth pressure, may develop very slowly, a very stable type of gauge must be used, while for the live load stresses, which are the more important, a type of gauge must be used which allows easy recording of the transient phenomena. The two strain gauges chosen were: an 8-inch mechanical extensometer (Fig. 13) and electrical resistance wire strain gauges, known as SR-4 gauges, together with amplifiers and a direct writing recorder (Fig. 14).

(b) Objects and Methods of Measurements

In accordance with the objectives already stated, of determining both the magnitude and the frequency of traffic load stresses, the two main types of strain measurements made were the following:

(a) Recording of strains in deck beams caused by very heavy loads (street-car, weighed T.T.C. crane car and weighed ready-mix concrete truck); and

(b) Recording of strains caused by normal traffic (street-car and motor traffic) over longer periods of time.

The following two special strain tests, on one beam each, were also made:

(a) Determination of impact effect of slow and fast moving street-cars going over rail crossings on strain in deck beam; and

(b) Determination of effectiveness of knee braces in reducing strain in the main deck beams.

In addition, the following three special investigations were made:

(a) Determination of the continuity effect in the stringers;
(b) Observation of the simultaneity of heavy loads (street-cars and ready-mix concrete trucks) on one beam during a concrete placing operation; and
(c) Some observations of strains caused by earth pressure.

(c) Experimental Results

(a) Strains in Deck Beams Caused by Known Loads

In order to determine the maximum stresses in the deck beams, a combination of loads corresponding closely to the assumed design load was used. It was found, however, that due to the traffic on Yonge Street it would be too difficult to position the combination of cars used, consisting of a T.T.C. crane car, a T.T.C. street-car, and two or more heavy trucks all at one time on one beam. Strains caused by these loads acting separately were, therefore, measured and added together, using the law of superposition, except for the crane car and the street-car the load effects of which were measured simultaneously. The law of superposition may not be strictly valid for the deck because the continuity effect of the stringers and the deck timbers may contribute to a progressively increasing distribution of the load on to the adjacent beams. Should this be the case, however, the resulting sum of strains (or stresses) could only be greater than the strain (or stress) produced by the combined load, and therefore the deck beams in reality would be safer than would appear from the test results.

According to the specifications of the Toronto Transportation Commission, the design load for the temporary street deck consists briefly of the following:

(1) A train on each street-car track, consisting of two or more 50-ton double truck cars, 40 feet long. Each axle load shall be 12.5 tons; axle spacings shall be 5, 20, and 5 feet; plus

(2) A column of trucks on each traffic lane of 10-foot width, consisting of one 20-ton truck, preceded and followed by 15-ton trucks; the load on the rear axle (or axles) shall be 4/5 of the total truck load and the spacing of the trucks shall be 44 feet.

Considering one deck beam alone in a simplified way the design load consists of the following double axle loads acting mainly on one beam

1 Truck	1 Street-car	1 Street-car	1 Truck
16 tons	25 tons	25 tons	16 tons

The load used in the experiments, although varying slightly from test to test, was approximately as follows:

1 Truck	1 Crane car	1 Street-car	1 Truck
17 tons	33 tons	17½ tons	17 tons

It can be seen that the magnitude of the test load with regard to its effect on bending moments was reasonably similar to the design load. Figure 15 shows part of the loads during a loading test.

The strains and resulting stresses measured in the various beams under the above-mentioned loads are presented in Table 1, whereby the following load cases are shown separately: one street-car north-bound; one street-car south-bound; crane car north-bound; crane car south-bound plus street-car south-bound; one concrete truck north-bound; one concrete truck south-bound; the last three loads combined. The maximum stresses obtained range from 5500 p.s.i. to 8500 p.s.i. Figure 16 shows a reproduction of two of the test records obtained during load test.

(b) Strains Caused by Normal Traffic

For each beam investigated strains caused by normal traffic on Yonge Street were recorded for various lengths of time, in order to obtain an idea of the frequency of occurrence of various loads. For the beam at Shuter Street a continuous twenty-four hour record of strains caused by all traffic was obtained. Figure 17 shows the distribution of strains (grouped by the numbers of lines of chart deflection) over the twenty-four hour period. Figure 18 presents the same measurements in a different manner: for typical hours of the day, the number of occurrences of the various strains is plotted. The predominance of the strains corresponding to the two loads of the street-cars is evident and explain why it was stated in the paragraph "Statistical Approach to the Design Problem" that the laws of statistics could not be applied here. Figure 16 shows the characteristic two pairs of strain peaks caused by the trucks of the front and the trailer car.

(c) Effect of Impact

The effect of impact is usually greatest at street intersections where street-cars passing over the rail crossings cause vibrations of the deck. This effect was determined in one case (for a beam at the intersection of Yonge and Wellington Streets) by comparing the strains caused by a street-car crossing the intersection at full and at very low speeds. The increase of strain due to full speed operation over the strain caused by static load was, for this beam, in the order of 30 per cent for one street-car alone. The impact effect of multiple loads was not determined. It was observed, however, that the heavier the load combination the more of its parts were moving slowly or even stationary. Consequently, the impact effect decreases with increasing load.

(d) Effectiveness of Knee Braces

Owing to the fact that it was possible to test one station section beam (north of Wellington St.) in three different conditions-- with knee braces, with one only, and with none-- under normal traffic, an approximate idea of the effectiveness of knee braces in reducing the centre span stresses has been obtained. It was not possible, however, to load the beam with the heavy load combination for all three conditions. Table 2 shows the stresses as determined from the strains measured for the loads of one street-car north-bound and one street-car south-bound for the above-mentioned three conditions. The difference between the strains caused by the north- and south-bound street-cars is due to the fact that the strain gauges could not be mounted exactly in the centre of the span, because of a spreader beam. The gauge was 10 inches east of the centre of the street as defined by the street-car rails.

The east knee brace was removed first as part of construction operations. The west knee brace was also removed while traffic on Yonge Street was still maintained. It was only cut near its lower end by an acetylene burner and in such a manner as to become effective under heavier loads. The gap created by the burner was just wide enough so that it would not be closed under the deflection caused by the load of one street-car.

The increase of stress due to removal of one knee brace was, on the average, close to 100 per cent; removal of both knee braces was approximately 200 per cent. If this same increase is applied to the stress due to the maximum load combination (6,200 p.s.i. obtained by superposition) a maximum fibre stress of close to 19,000 p.s.i. would have been reached.

The stresses in one of the knee braces of the above-mentioned beam were also measured. The conclusion that the knee brace would experience the highest stresses near mid-span on the underside was confirmed by taking spot readings at various points of the knee brace by means of the 8-inch mechanical extensometer. Electrical strain gauges were then attached only at mid-span of the brace and the results shown in Table 2 were attained by the gauge on the underside.

The maximum stress in the knee brace, caused by the usual heavy load combination totalling $84\frac{1}{2}$ tons, was 8,550 p.s.i. compared to 6,200 p.s.i. in the deck beam. Both these figures were obtained by superposition. Consequently, the knee brace was underdesigned compared to the beam, in fact considerably more than appears from the comparison of the stress values because of the danger of buckling present in the knee brace.

(e) Continuity Effect of the Stringers

The low values of maximum stress obtained in the deck beams lead to the conclusion that these beams receive considerable load relief, compared to strict simple beam action, by distribution of load, to varying degrees, to the adjacent beams through stringers, rails, and timbers. This load relief is caused by the fact that the greater deflection of the loaded beam except when all beams are equally loaded which is never the case with the spacing of beams and loads used on this project results in a tendency of the stringers, rails and partly also the timbers to bridge over this beam. The partial fixity of the ends of the deck beams (welded brackets) also contributes to the load relief. Because of the spacing of the beams and loads on this project, it is never possible for all beams to be loaded equally.

The stringers act partly as continuous beams through the webs of the deck beams to which they are welded by means of brackets. The transmission of bending moments through the web of the heavy deck beams is, of course, impeded by the torsional stiffness of the deck beams. As can be seen from the strain lines of Fig. 19, however, some negative moments do act in the non-loaded spans adjacent to the loaded span. The strain readings were taken by means of an 8-inch mechanical extensometer on two lines of stringers over two spans, at the quarter- and mid-span points. The load used consisted of the T.T.C. crane car loaded to approximately 32 tons per truck, i.e., exceeding the specified design load by 7 tons. For the measurements the deck planks covering the ties were removed and the person reading the extensometer was standing just below the deck on the partly completed backfill.

The maximum stress recorded in the stringers was 9,400 p.s.i. which is 25 per cent below the value of 12,600 p.s.i. computed for the same steel section acting as a simple beam. The greatest stress measured in an area of negative moment was approximately 1,000 p.s.i.

From the magnitude of strains in the stringers for the load stradling a deck beam it can be seen that always a considerable portion of the load of a truck, of a street-car or crane car is distributed to the adjacent beam.

(f) Coincidence of Heavy Loads During Concrete Placing

The likelihood of occurrence of heavy load combinations was greatest during concrete placing operations, when, in addition to two street-cars crossing on one beam, there might be two ready-mix concrete trucks standing on the side lanes on the same beam. It is not surprising that during the accurate observation made of one complete concrete placing operation for a roof section, approximately 100 feet south of Dundas Street, during about five hours, not once was a beam loaded simultaneously by two street-cars and two concrete trucks.

This becomes understandable when one considers that only once every two to two and one-half hours do two street-cars cross on the same beam which would double the strain caused by one street-car. This was established from the records obtained by means of the strain analyzer equipment.

During the above-mentioned observation of load combinations occurring during a concrete placing operation the following frequencies of loads were found:

2 street-cars plus 2 concrete trucks exactly on the same beam - 0 times.

1 street-car plus 2 concrete trucks exactly on the same beam - 0 times.

1 street-car plus 2 concrete trucks with centre of rear axles at average distance of 1 ft. from the beam - 0 times.

1 street-car plus 2 concrete trucks average distance of 2 feet - once.

1 street-car plus 2 concrete trucks average distance of 3 feet - twice.

1 street-car plus 2 concrete trucks average distance of 4 feet - 8 times.

1 street-car plus 2 concrete trucks average distance of 5 feet - 7 times.

It follows that even during concrete placing operations, load combinations consisting of two street-cars and two concrete trucks acting simultaneously on the same beam are extremely rare, although definitely possible.

(g) Strains Caused by Earth Pressure

The attempt to determine the axial load in deck beams and also in steel struts by means of the mechanical extensometer was only partly successful. Taking readings on beams which were almost inaccessible under the street deck as well as obtaining the zero readings was often very difficult. The inaccuracies inherent to long-term measurements (deterioration of the small drill holes in the beams, etc.) affected the quality of the readings. Some difficulties were also encountered at first due to the fact that the extensometer was made of ordinary steel (and not of Invar as indicated by one authority) and, therefore, was found to be sensitive to the heat of the hands of the person taking the readings.

In Fig. 20 the results of the strain measurements on the knee-braced beam north of Wellington Street (Stations 115 and 44) are shown. At the time of the last readings (when the slab and the walls of the subway had been completed) the axial stress in the beam had reached a value of the order of magnitude of 5,000 p.s.i., corresponding to a force of 130 tons.

Out of general interest the results of some strain measurements taken on steel struts, in the same area, are also shown (Fig. 21). The load on the struts, varying roughly between 20 and 30 tons, was not very large. This is in line with the relatively late installation of the struts. In view of the stiff plastic nature of the soil, it was possible for the contractor to determine the need for struts in most locations on the basis of measurements of the distance of opposite soldier piles by means of a measuring tape. If any excessive inward movement of the piles was detected, struts were installed.

The danger of buckling in a horizontal direction of both the deck beams and the struts, was considerably reduced by effective use of spreaders and tie rods, and also of the stringers connecting the deck beams.

5. DISCUSSION OF RESULTS

(a) Low Maximum Stresses

The two most striking aspects of the results are the low value of stresses obtained under a heavy load combination corresponding closely to the design load and the infrequency of heavy loading by the traffic on the deck. It is believed that the low stresses in the deck beams were principally due to the fact that they do not act as simple beams. Two reasons for this are:

(a) Due to the load relief resulting from the continuity effect of stringers, rails, and deck timbers, the maximum load actually carried by one beam does not correspond to the combined axle loads acting on this beam;

(b) The welded connections between the deck beams and the cap beams and piles introduce some end fixity into the beams.

The amount of axial load due to earth pressure that is transmitted from the soldier piles to the deck beams is limited by the conditions present. The earth pressure acts mainly as a horizontal load on the piles, which are supported at the top by the deck beams, at the bottom by the embedment in the soil and, in some cases, in between by struts. The flexural strength of the steel piles, combined with their unsupported vertical span below the deck beam, limits the reaction in the deck beam and, therefore, the stresses due to earth pressure. An estimate for an average deck beam, with struts 10 feet below it, yields an average compressive stress of less than 3,000 p.s.i. even when the piles are loaded to yield (40,000 p.s.i. fibre stress). Actually this force is introduced along the bottom of the deck beam, resulting in a favourable eccentric loading, i.e., a tendency to compensate the stresses due to the deck load. In knee-braced deck beams the axial load can become greater because the knee braces, in assuming part of the role of the struts, transfer a greater percentage of the earth pressure to the deck beam.

(b) Infrequency of Heavy Loads

As the records of strains in the deck beams caused by normal traffic show, the other notable aspect of the results is the infrequency of large strains or stresses. It is probable that the majority of the deck beams on this project will never normally experience stresses exceeding three-quarters of the stress obtained under the heavy experimental load combination used, and be subjected to this stress only very seldom, i.e., only when the T.T.C. crane car is used on Yonge St. In the absence of the crane car, the probability of relatively heavy loads acting simultaneously on the same beam is greatest during concrete placing operations. Even then, however, very few beams will experience the full combined load of two street-cars plus two full concrete trucks, as the observation of vehicle movements made during a concrete placing operation showed.

(c) Improvement of Economy in Future Designs

One of the principal objectives of this study was to see in what direction improvements might be effective in future designs of the same type of temporary deck structure. The design loads used for this part of the T.T.C. Subway project were necessarily used in the absence of such specific information as this Report presents. Nothing in this Report is to be taken as any indication of criticism of this quite proper approach to an unusual design problem. Should, however, a similar temporary structure have to be designed in the future, in Toronto or elsewhere, it does now seem possible for some additional economy to be introduced safely into the proportioning of the deck system.

In the first place, it would seem practicable to make some allowance, possibly to the extent of a reduction of 30 per cent in the assumed design load on any one beam, for the continuity which obviously exists even in such a temporary structure as that which was investigated in Toronto.

To allow for the infrequency of heavy load combinations a further decrease of the design load would seem possible because the probability of occurrence of the heavy load combinations is small. In fact a considerable saving might be obtained by regulating the movement of the T.T.C. crane car, by issuing instructions to the driver with regard to passing other vehicles on the street deck. If, in this way, the driver were not allowed to pass a street-car and two heavy trucks at the same time, consideration of a further reduction in the design load would be possible. Even if the driver of the crane car neglected to observe the instructions, the factor of safety inherent to the allowable design stress would be ample to take care of the slight overloading.

The investigation of the effectiveness of the knee braces showed the great benefit obtained by these braces in reducing the bending moments in the deck beams. The knee braces would seem, therefore, to be of great value in saving steel in the deck beams, possibly also in the box sections of the subway, when circumstances allow their use. The knee braces also help to reduce the need for strutting by transferring a greater percentage of the earth pressure from the piles to the deck beams. This force should also be taken into account in the design of deck beams for similar structures.

ACKNOWLEDGEMENTS

Much assistance has been received by the author during his work. It would be impossible to list all those who have given a helpful hand in the work itself or in the form of suggestions during discussions. To all sincere gratitude is expressed.

Special mention, however, must be made of the co-operation of the Toronto Transportation Commission and the staff of the Testing Subsection of the Rapid Transit Department in particular, without whose help this work could not have been carried out. The co-operation of the General Contractor for S-1 and S-2, Pitts, Johnson, Drake and Perini, is also acknowledged. Gratitude is also expressed for the many helpful suggestions and the loan of some equipment which was received from the staff of the Research Laboratories of the Hydro-Electric Power Commission of Ontario.

The author wishes to record his gratitude for the continued assistance, encouragement, and understanding received during this work from Mr. R.F. Legget and a large number of the staff of the Division of Building Research.

APPENDIX A

Equipment Used for Strain Measurements

Extensometer

The extensometer, in principle, is a device for measuring the change in distance between pairs of small holes drilled into the steel structure. The extensometer, shown in Fig. 13, consists of two conical steel points mounted on a metal frame, which carries a dial gauge actuated by a lever. One of the two conical points is fixed, the other movable over a range of 3/100 inch. This movable point is part of the lever which actuates the dial gauge with a lever ratio of 1:10. Each unit on the dial gauge, which is graduated in 1/1000 inch, therefore, represents a movement of the point of 1/10,000 inch. With a gauge length of 8 inches, this is a strain of 12.5 micro inches/inch, or a stress of 375 pounds per square inch in steel with the usual modulus of elasticity.

As the Metzger extensometer is not made of Invar but of steel, it is sensitive to temperature changes. If, however, the coefficient of thermal expansion of the extensometer is the same as that of the structure and if the extensometer is at all times at the same temperature as the structure, no correction of the readings is necessary for temperature expansion. A "standard bar" for reference readings should, however, be used in all cases. It should be laid on the structure for a sufficient time to allow it to assume the temperature of the structure. The standard bar is also used to compensate for possible changes in the length of the extensometer which might be caused by accidental bending of the conical points or in case of repairs. The punch bar, which is supplied with each extensometer, was used as standard bar by taking readings on the holes drilled for this purpose near the set screws.

Electrical Resistance Strain Gauges

SR-4 strain gauges were used for picking up strains in the deck beams due to traffic loads. This type of gauge operates on the principle that the electrical resistance of a given wire changes with a change in a length such as may be produced by tensile or compressive stress of the wire. A stretching of the wire results in an increase of electrical resistance due to both the increased length and the reduced cross-section. This change of resistance, other factors such as temperature remaining constant, can be calibrated in terms of strain. The gauge consists of a grid of fine alloy wire, bonded to a paper base, about the size of a postage stamp. The gauge was bonded to the structure at the desired place, after the steel surface has been prepared by means of a grinder and various grades of emery paper. The lead wires of the gauges were soldered to the wires of a cable leading to the recording equipment and the gauge covered by a coating of wax to protect it from moisture.

The SR-4 gauge will respond to compressive as well as to tensile strains. Since the full length of wire is bonded, the wire cannot buckle and does not need to be preloaded. As already mentioned, the stretching of the gauge results in an increase of resistance due to the increase of the length of the wire and the decrease of the cross-section. It has been found that the change of resistance is larger than would be expected from the pure geometrical change of the wire. The magnification factor expressed by $\Delta R/R$ over $\Delta L/L$, where R means electrical resistance and L length of the wire, is called the gauge factor. It varies considerably for different materials, and slightly for each batch of manufactured gauges. Therefore each package of gauge carries a value for the gauge factor which, for the common type of SR-4 gauge used in this project, is around 2.05.

Naturally some form of temperature compensation has to be employed in order to eliminate changes of resistance of the wire due to temperature changes of the wire and due to strains in the structure resulting from thermal expansion. For this purpose a second SR-4 gauge, known as a "dummy gauge" is mounted on an unstrained piece of the material of the structure located near the "active gauge" and used in the compensating arm of the Wheatstone bridge of the measuring circuit.

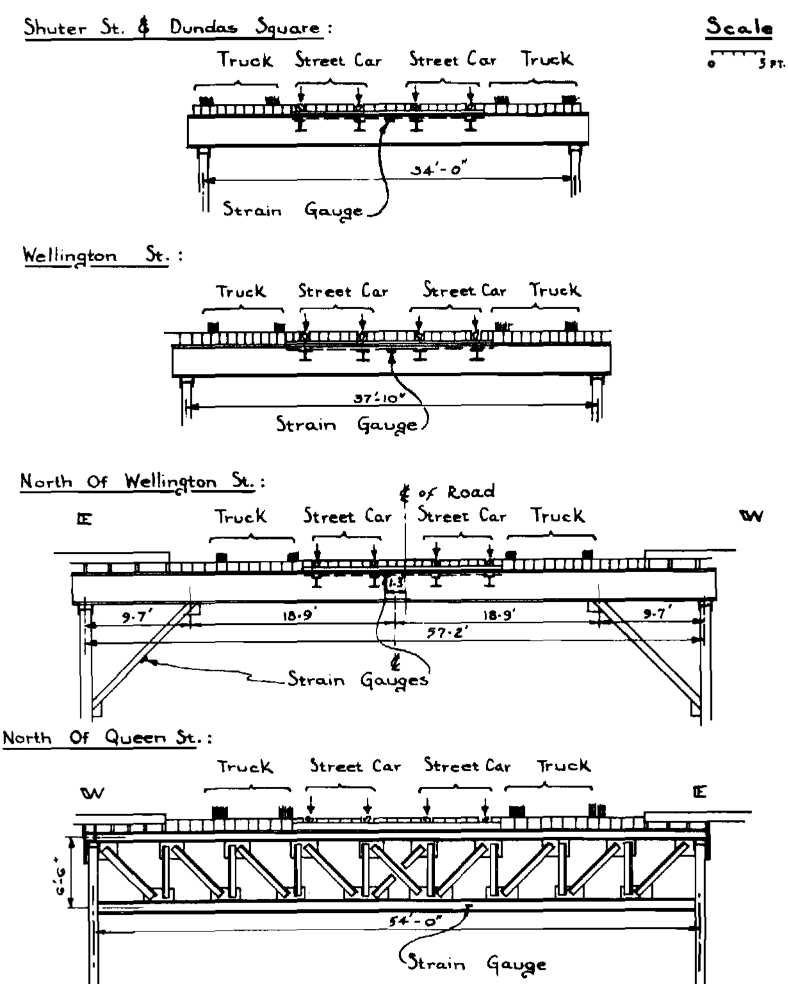
The two pairs of lead wires, from the active and the dummy gauges, are carried as a shielded four-conductor cable to the recording equipment located above ground in a small hut (Fig. 15). This equipment, which consisted mainly of two bridge balancing units and amplifiers and a two-channel direct-writing recorder, was chosen after a careful study of commercially available instruments. The convenience of direct writing recording (in contrast to photographic recording) and the wide range of paper speeds, were the main factors in favour of the choice of the strain analyzer used because it had been established that the frequency response of the direct writing method was sufficient.

The strain analyzer contains two arms of a Wheatstone bridge, connected to a high frequency carrier supply (2,000 cycles per second). The other two arms of the bridge are the active and the dummy gauge. The bridge is balanced by the resistance and phase controls on the panel of the amplifier. The bridge output is amplified, demodulated and fed into a d-c. amplifier and from there into the magnetic pen motor of the recorder. When the active gauge is subjected to a strain, the "out-of-balance" of the Wheatstone bridge shows as a deflection of the chosen zero-line on the chart of the recorder. The strain analyzer is calibrated directly in terms of strains, so that for the SR-4 strain gauge of 120 ohms, strain can be read directly in micro inches per inch from the chart deflection. The overall gain can readily be checked by a control on the amplifier which connects an internal calibrating resistor into the bridge circuit and be adjusted if necessary. For various applications of the equipment with different orders of magnitude of strain, an attenuator permits a choice of sensitivities, from 10 to 2,000 micro-inches per inch corresponding to a deflection of one line on the chart paper, which has a width of 40 lines. Magnitude as well as direction (tension or compression) of the strain can be read from the chart and also both static and dynamics strains (up to approximately 80 to 100 cycles per second). The speed of the chart paper can be selected easily by a gear shift from the following values: 50, 250, 1250 mm/hour, 5, 25 and 125 mm/sec. corresponding roughly to 2, 10, 50, 720, 3,600 and 18,000 inches/hour. The strain analyzer operates on 60-cycle power. Since Toronto is still in the 25 cycle area, a portable gasoline engine driven generator was used as a power supply.

SUBWAY SECTION	BOX SECTION	BOX SECTION	BOX SECTION	STATION SECTION	STATION SECTION
LOCATION	AT SHUTER ST.	AT WELLINGTON ST.	AT DUNDAS SQ.	NORTH OF WELLINGTON	NORTH OF QUEEN ST.
STATION	138 + 35	114 + 35	144 + 00	115 + 44	132 + 60
TYPE	I BEAM	I BEAM	I BEAM	I BEAM KNEE BRACE	TRUSS
STEEL SECTION	36" WF 182#	36" WF 230#	36" WF 182#	36" WF 182#	6'-6" LENGTH 12" WF 99#
SPARE	34'	37'-10"	34'		54'
SPACING OF BEAMS	12'	SOUTH 6' NORTH 12'	12'	12'	12'
DATE OF TEST	1 & 2 MAR. 1951	12 & 18 JAN. 1951	17 JULY & 24 AUG. 51	12 DEC. 1950	17 JULY & 27 AUG. 51
TYPE OF STRAIN GAUGE	SR-4, A-1	SR-4, A-1	SR-4, A-1	SR-4, A-1	SR-4, A-1
GAUGE FACTOR	2.05	2.05	2.05	2.05	2.05
GAUGE TO EXTR. FIBRE	4" FROM TOP	4" FROM TOP	4" FROM TOP	4" FROM TOP	CENTER of BOTTOM CHORD
GAUGE TO ℄ OF BEAM	2" (WEST)	2" (WEST)		10" (EAST)	6'-6" (EAST)
℄ ROAD TO ℄ OF BEAM	2" (WEST)	11" (WEST)		5" (WEST)	
INSTRUMENT ATTENUATION					
STRAIN: 1 LINE ON CHART =	10 μ IN/INCH	10 μ IN/INCH	10 μ IN/INCH	10 μ IN/INCH	10 μ IN/INCH
STRESS: 1 LINE ON CHART =	300 PSI	300 PSI	300 PSI	300 PSI	300 PSI

LOADS ON DECK BEAM ⇩	STRAIN (LINES)	STRESS AT GAUGE (PSI)	STRESS AT EXTR.F. (PSI)	STRAIN (LINES)	STRESS AT GAUGE (PSI)	STRESS AT EXTR.F. (PSI)	STRAIN (LINES)	STRESS AT GAUGE (PSI)	STRESS AT EXTR.F. (PSI)	STRAIN (LINES)	STRESS AT GAUGE (PSI)	STRESS AT EXTR.F. (PSI)	STRAIN (LINES)	STRESS AT GAUGE (PSI)	STRESS AT EXTR.F. (PSI)
1 STREET CAR NORTH (LOADED, 17½ TONS/TRUCK)	5½	1650	2100	3½	1050	1350	4½	1350	1750	3	900	1150	4½	1350	1350
1 STREET CAR SOUTH (LOADED, 17½ TONS/TRUCK)	5½	1650	2100	3	900	1050	5	1500	1950	2	600	750	3	900	900
1 CRANE CAR NORTH (LOADED, 33 TONS/TRUCK)	13	3900	5000	8½	2550	3300	13	3900	5000	10½	3150	4050	12	3600	3600
CRANE CAR N + STREET CAR S. (LOADED, 50½ TONS)	17½	5250	6750	10½	3150	4050				12	3600	4650			
CONCRETE TRUCK NORTH (ON SIDE LANE, 17 TONS)	2	600	775	2¼	675	850	2	600	750	3	900	1150	3 ASSUMED		
CONCRETE TRUCK SOUTH (ON SIDE LANE, 17 TONS)	2	600	775	1½	450	600				1	300	400	2 ASSUMED		
MAX. LOAD (LAST THREE) 84½ TONS (BY SUPERPOS.)	21½	6450	<u>8300</u>	14¼	4275	<u>5500</u>	22	6600	<u>8500</u>	16	4800	<u>6200</u>	20	6000	<u>6000</u>
1 STREET CAR NORTH, SLOW (FOR MIN. IMPACT)				2¾	825	1050									
1 STREET CAR SOUTH, SLOW (FOR MIN. IMPACT)				2¼	675	850									

TABLE 1 STRESSES IN DECK BEAMS



TYPES OF BEAMS TESTED

SUBWAY SECTION	Station section
LOCATION	North of Wellington Street
STATION	115 + 44
TYPE	I beam, knee-braced
STEEL SECTION	Beam: 36" WF 182#, knee braces: 8" WF 40#
SPAN	Total 57'-2", between knee braces 37'-10"
SPACING of DECK BEAMS	12'

	STRAINS & STRESSES IN											
	DECK BEAM WITH BOTH KNEE BRACES						DECK BEAM ONLY ONE BRACE (E BRACE REMOVED)			DECK BEAM BOTH BRACES REMOVED		
	DECK BEAM			KNEE BRACE								
	STRAIN LINES*	STRESS AT GAUGE PSI	STRESS AT EXTR. F. PSI	STRAIN LINES	STRESS AT GAUGE PSI	STRESS AT EXTR. F. PSI	STRAIN LINES	STRESS AT GAUGE PSI	STRESS AT EXTR. F. PSI	STRAIN LINES	STRESS AT GAUGE PSI	STRESS AT EXTR. F. PSI
1 STREET CAR NORTH (LOADED 17½ TONS PER TRUCK.)	3	900	1150	5	1500	1500	5½	1650	2100	8	2400	3100
1 STREET CAR SOUTH (LOADED 17½ TONS PER TRUCK)	2	600	750	3½	1050	1050	4	1200	1500	6½	1950	2500
1 CRANE CAR NORTH (LOADED 33 TONS PER TRUCK)	10½	3150	4050	14	4200	4200	83% &			167% &		
1 CRANE CAR N. + 1 STREET CAR (LOADED 50½ TONS)	12	3600	4650	15½	4650	4650	100%			225%		
1 CONCRETE TRUCK NORTH (ON SIDE LANE, 17 TONS)	3	900	1150	9	2700	2700						
1 CONCRETE TRUCK SOUTH (ON SIDE LANE, 17 TONS)	1	300	400	4	1200	1200						
MAX. LOAD LAST THREE, BY SUPERPOSITION 84½ TONS	16	4800	6200	28½	8550	8550						

INCREASE of STRAINS COMPARED TO BEAM WITH BOTH KNEE BRACES.

* SEE TABLE 1

TABLE 2 : STRESSES IN KNEE-BRACED DECK BEAM

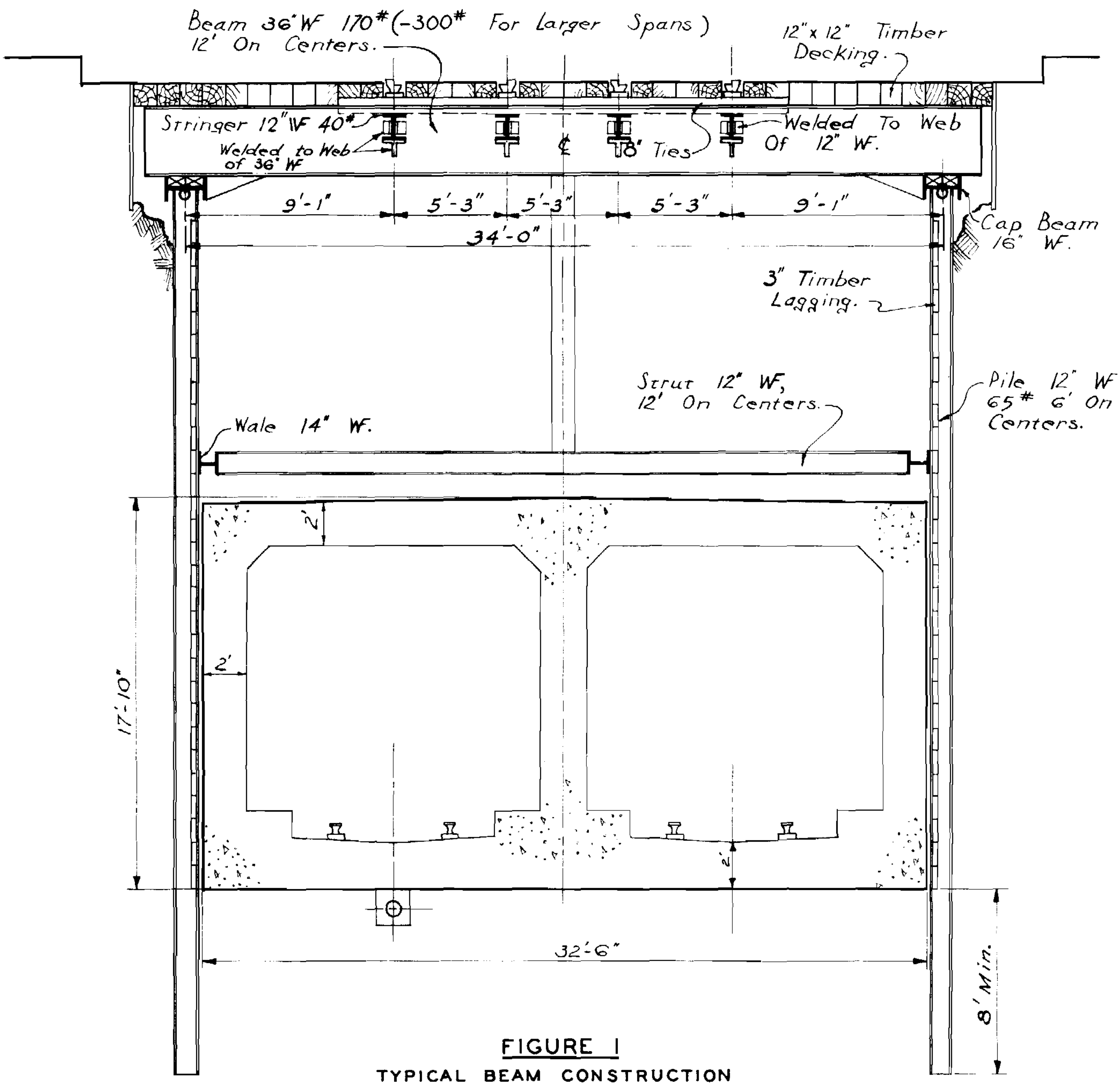


FIGURE 1

TYPICAL BEAM CONSTRUCTION FOR BOX SECTION OF SUBWAY

SCALE

0 1 2 3 4 5 FT.

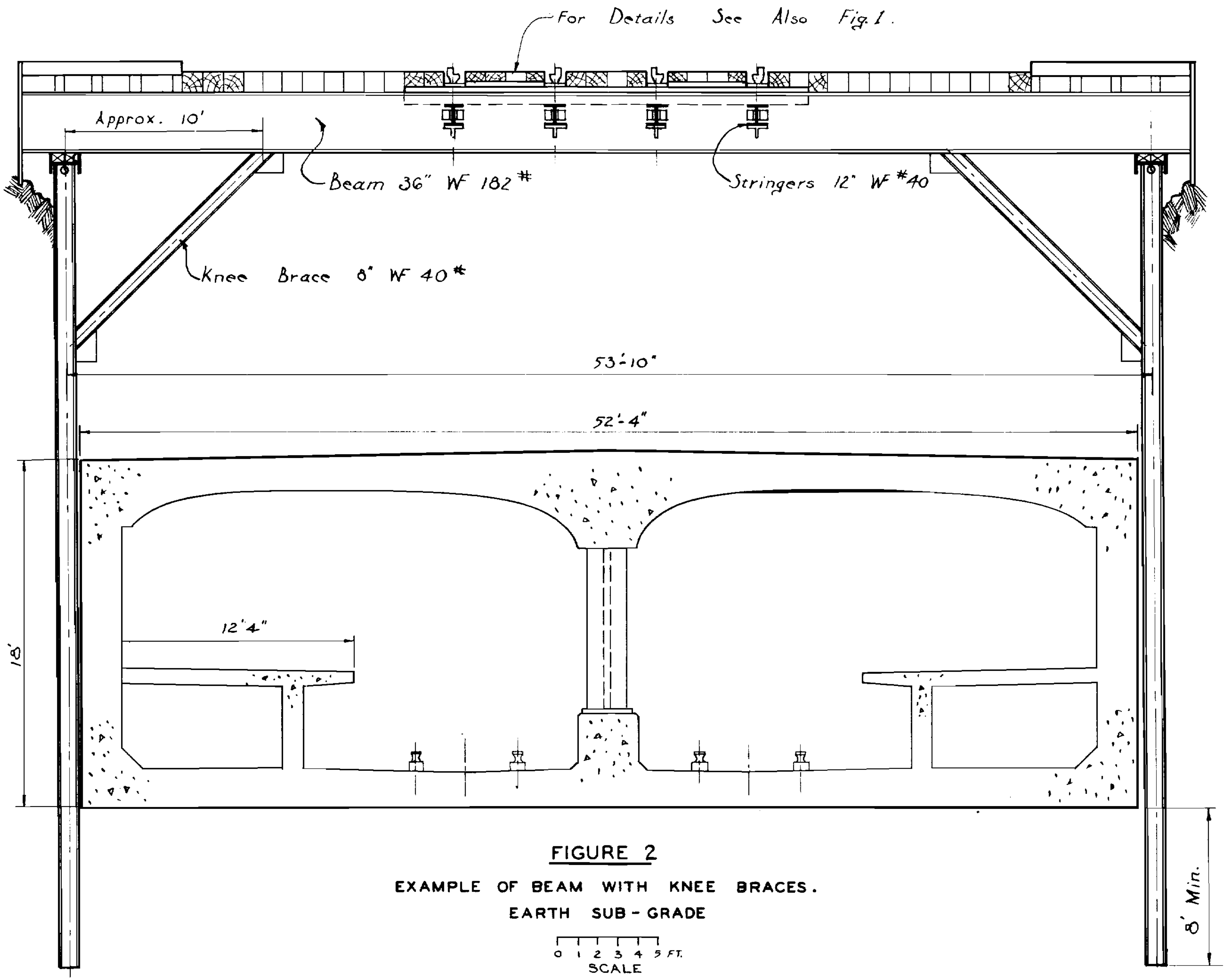


FIGURE 2

EXAMPLE OF BEAM WITH KNEE BRACES.

EARTH SUB-GRADE

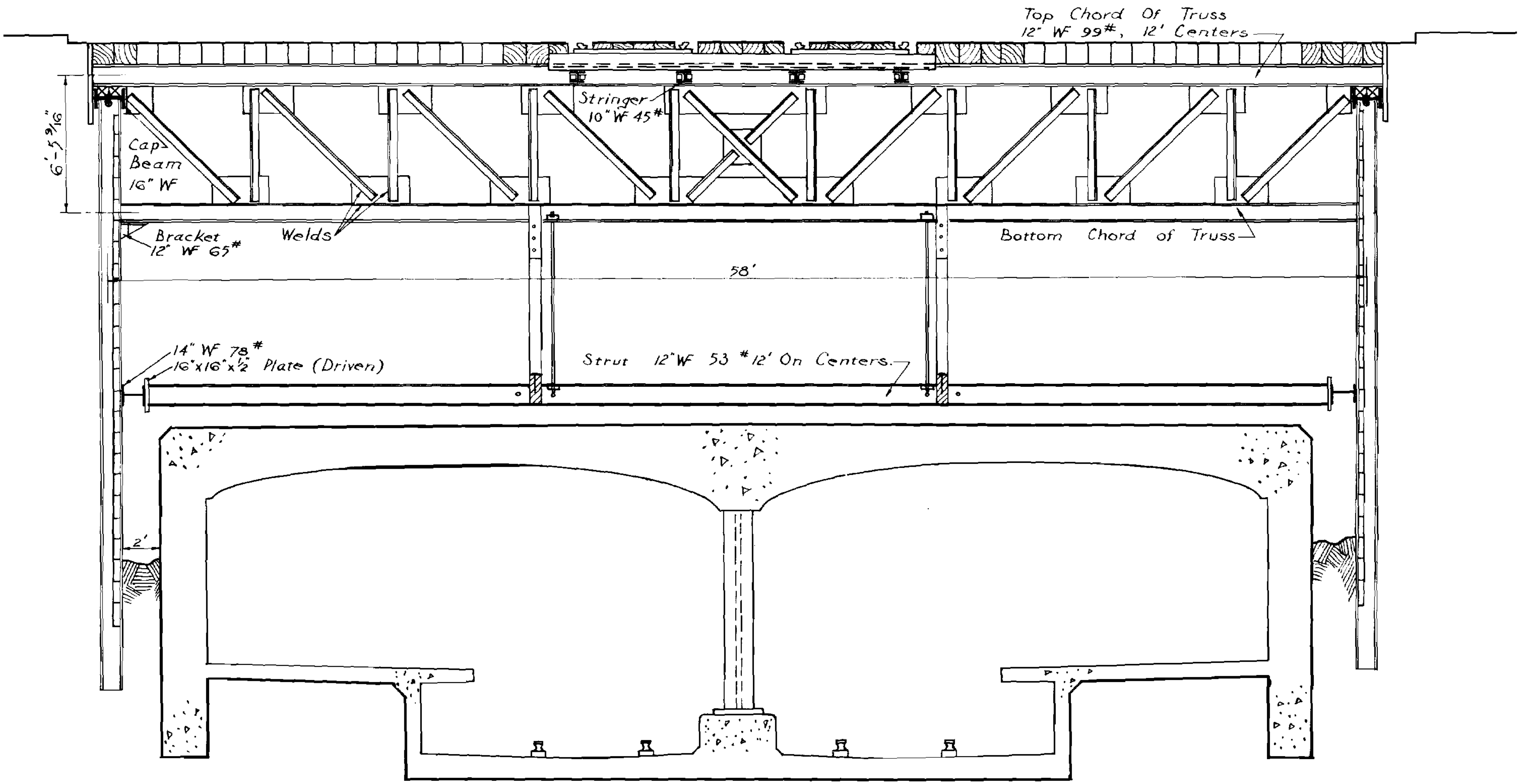


FIG. 3

EXAMPLE OF TRUSS. ROCK SUB-GRADE

SCALE

0 1 2 3 4 5 FT.

FIG. 4 DRIVING of SOLDIER PILES. (STEEL H PILES)

FIG. 5 PILES DRIVEN TO REFUSAL (BED ROCK AT 20 FT. DEPTH.

FIG. 6 EXCAVATION of TOP LIFT AND EXPOSURE of UTILITIES.

FIG. 7 SUPPORTING UTILITIES BY TIMBERS PRIOR TO SUSPENDING THEM UNDER THE ROAD DECK. PART of PILES CUT AT CORRECT LEVEL.

FIG. 8 PLACING of 36" WF I BEAMS ON CAPPED SOLDIER PILES AND of 12"x12" TIMBER PLANKING.

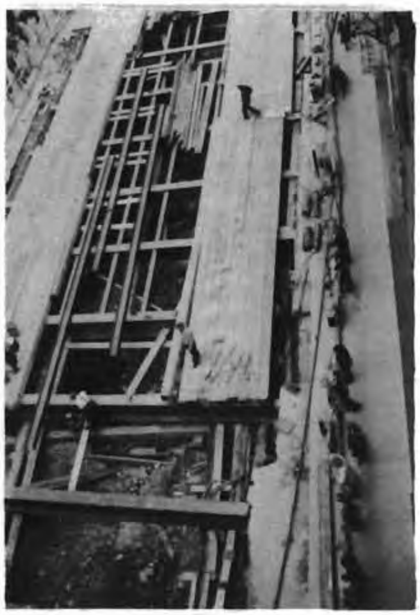


FIG. 9 GENERAL VIEW of CONSTRUCTION of DECK. NOTE PART of STRINGERS IN PLACE UNDER CENTER LANES.

FIG. 10 TIMBER PLANKING CUT TO LENGTH. PLACING of TIES AND RAILS. NOTE SUSPENDED WATER MAIN

FIG. 11 TEMPORARY ROAD DECK COMPLETED. NOTE INSTRUMENT HUT FOR STRAIN MEASUREMENTS AT RIGHT.

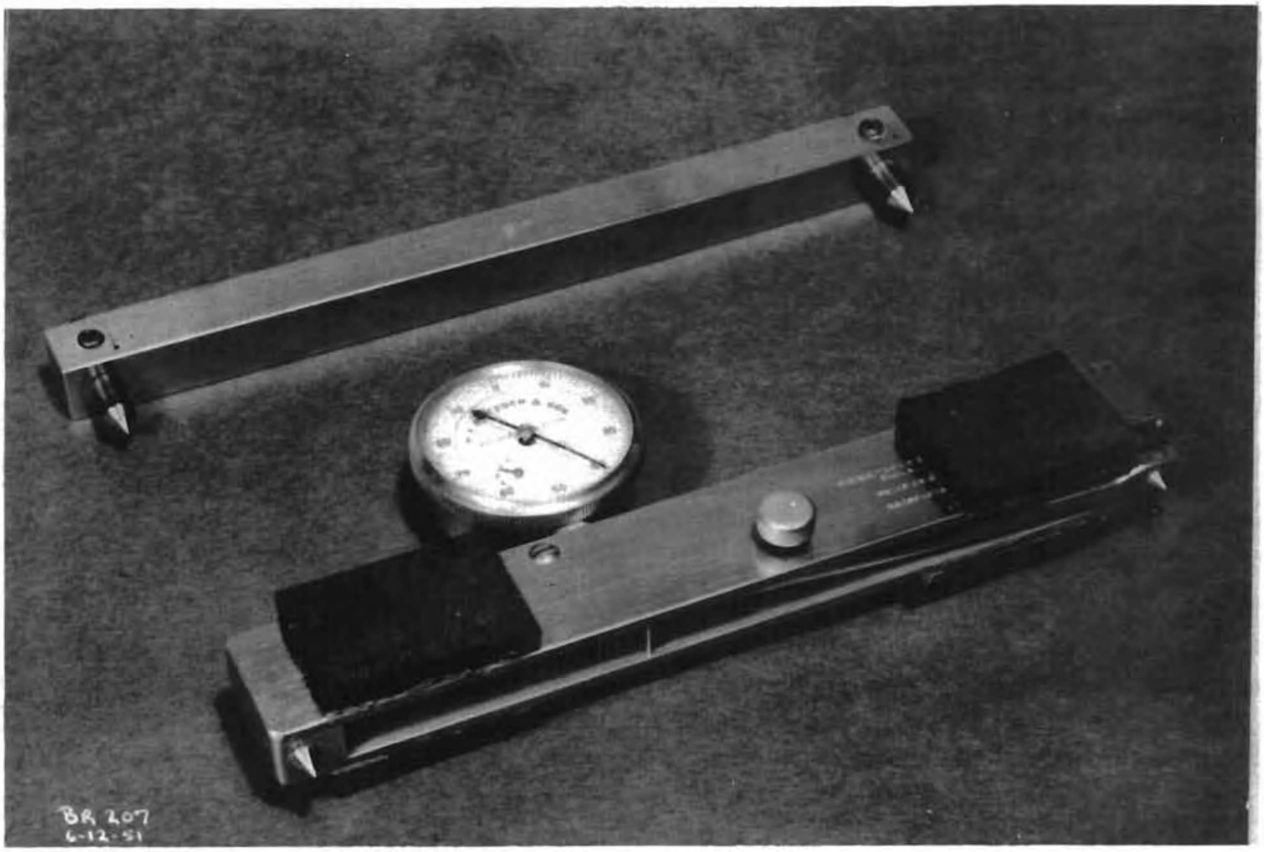


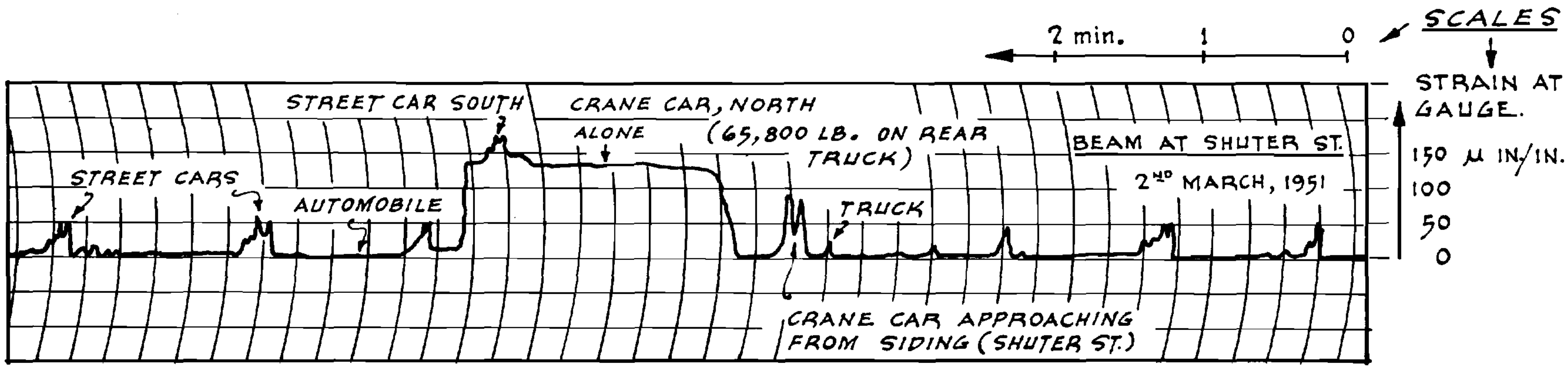
FIGURE 12

8 INCH EXTENSOMETER

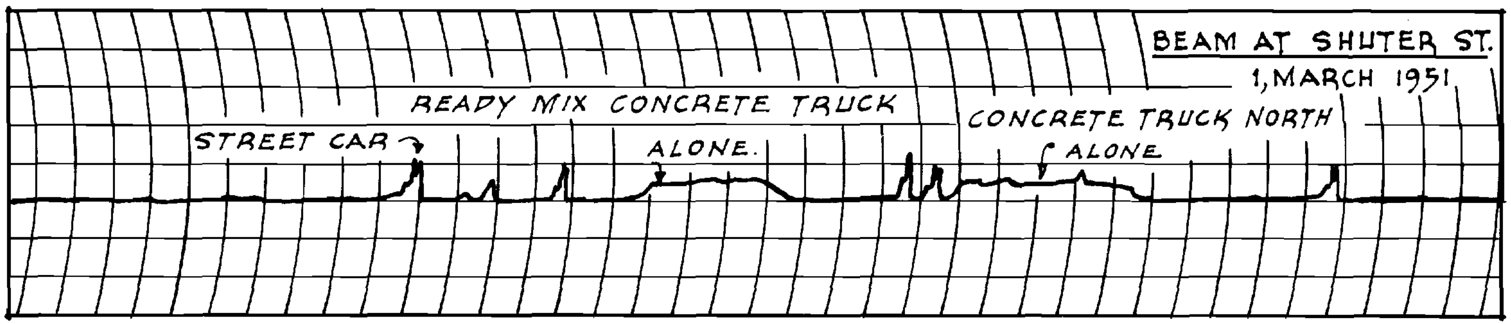
FIG. 13 STRAIN ANALYZER. TWO AMPLIFIERS AND TWO-CHANNEL DIRECT WRITING RECORDER.

FIG. 14 INSTRUMENT HUT ON SIDEWALK. 60 CYCLE POWER GENERATOR AT LOWER LEFT.

FIG. 15 PART of LOADING TEST (STREET CAR AND CRANE CAR)



LOADING TEST WITH WEIGHED T.T.C. CRANE CAR WESTBOUND PLUS STREET CAR SOUTHBOUND (PASSING WHILE CRANE CAR STANDS IN CORRECT POSITION)

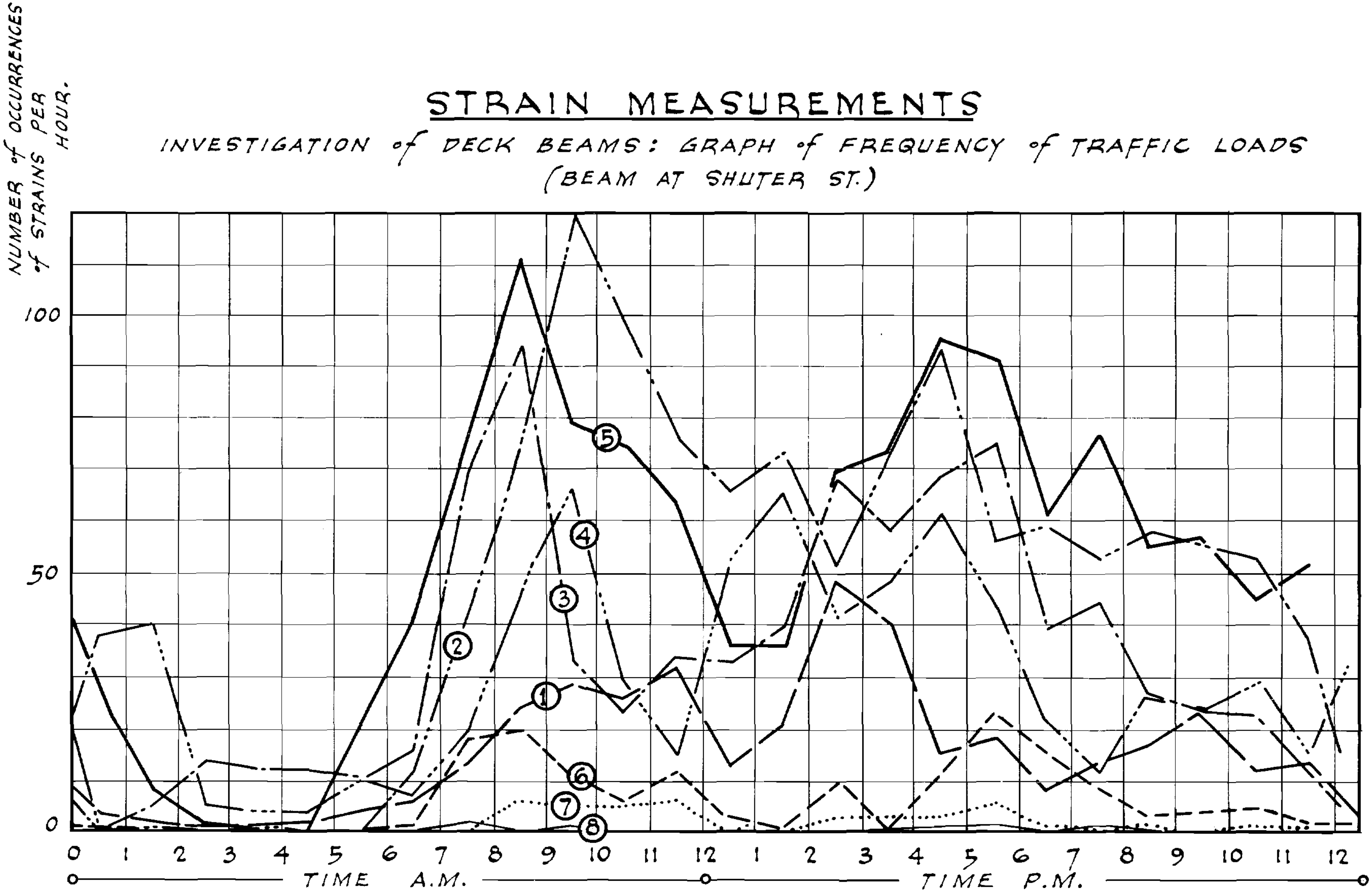


LOADING TEST WITH WEIGHED READY MIX CONCRETE TRUCK ON TRAFFIC LANES, BOTH NORTH AND SOUTHBOUND.

FIG. 16 PART of STRAIN ANALYZER RECORDS of LOADING TESTS ON BEAM AT SHUTER ST.

STRAIN MEASUREMENTS

INVESTIGATION of DECK BEAMS: GRAPH of FREQUENCY of TRAFFIC LOADS
(BEAM AT SHUTER ST.)



LEGEND	STRAIN READINGS	FIBRE STRESS AT CENTER of SPAN.	LEGEND	STRAIN READINGS	FIBRE STRESS AT CENTER of SPAN
— — —	① LINES	190 - 580 PSI	———	⑤ LINES	1730 - 2120 PSI
—-··—	② "	580 - 960 "	- - - - - -	⑥ "	2120 - 2510 "
—-·—	③ "	960 - 1350 "	··········	⑦ "	2510 - 2890 "
—-···—	④ "	1350 - 1730 "	———	⑧ "	2890 - 3280 "

FIG. 17

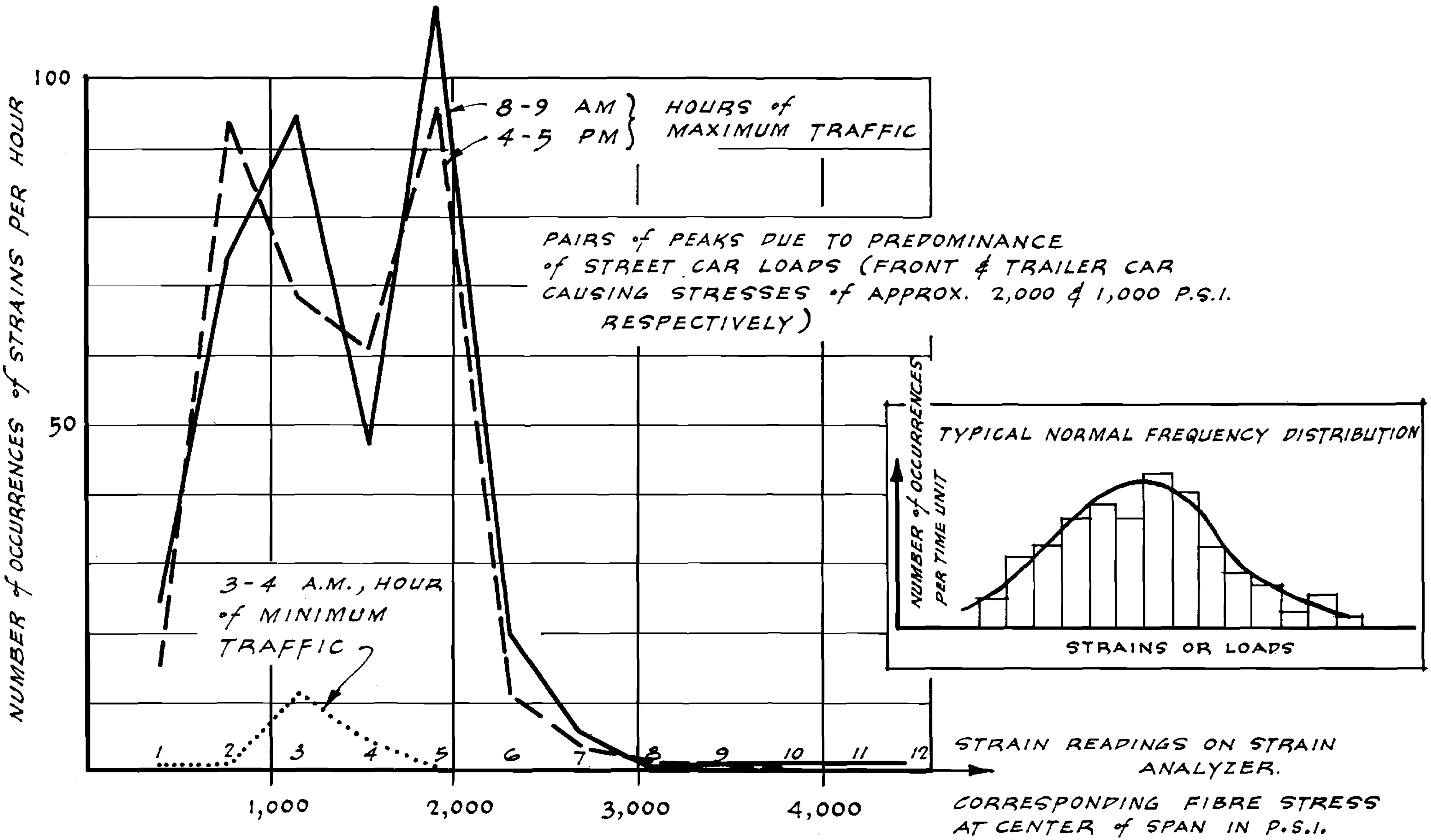


FIG. 18 TYPICAL FREQUENCY DISTRIBUTIONS of TRAFFIC LOADS

Obtained from strain measurement records
taken over 24 hour period on 28TH Feb./1ST Mar. 1951
BEAM AT SHUTER ST.

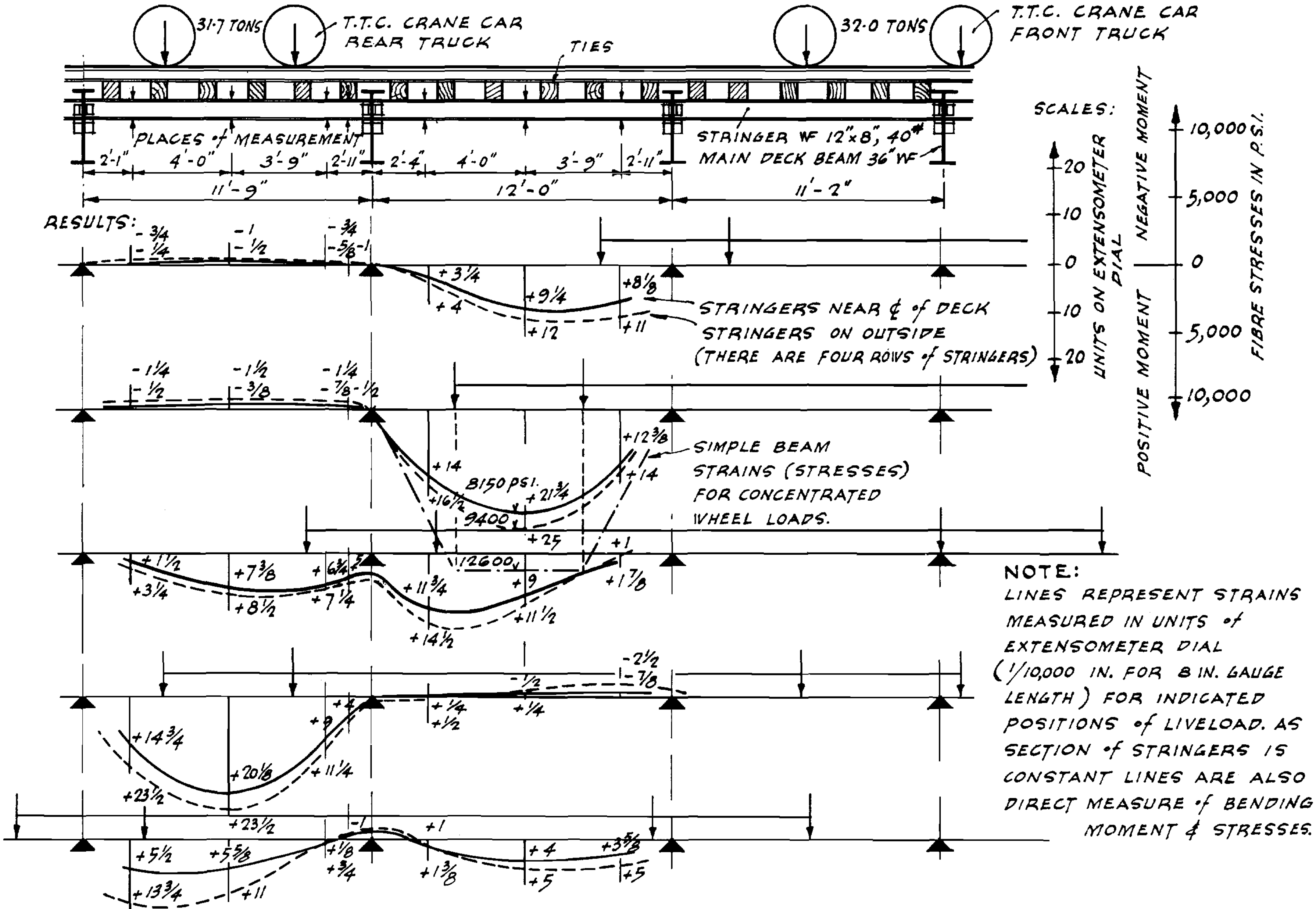


FIG. 19 STRAIN MEASUREMENTS ON STRINGERS, "TRACK BEAMS," BY MEANS of 8 IN. EXTENSOMETER.

T.N.B. SEPT. 1952

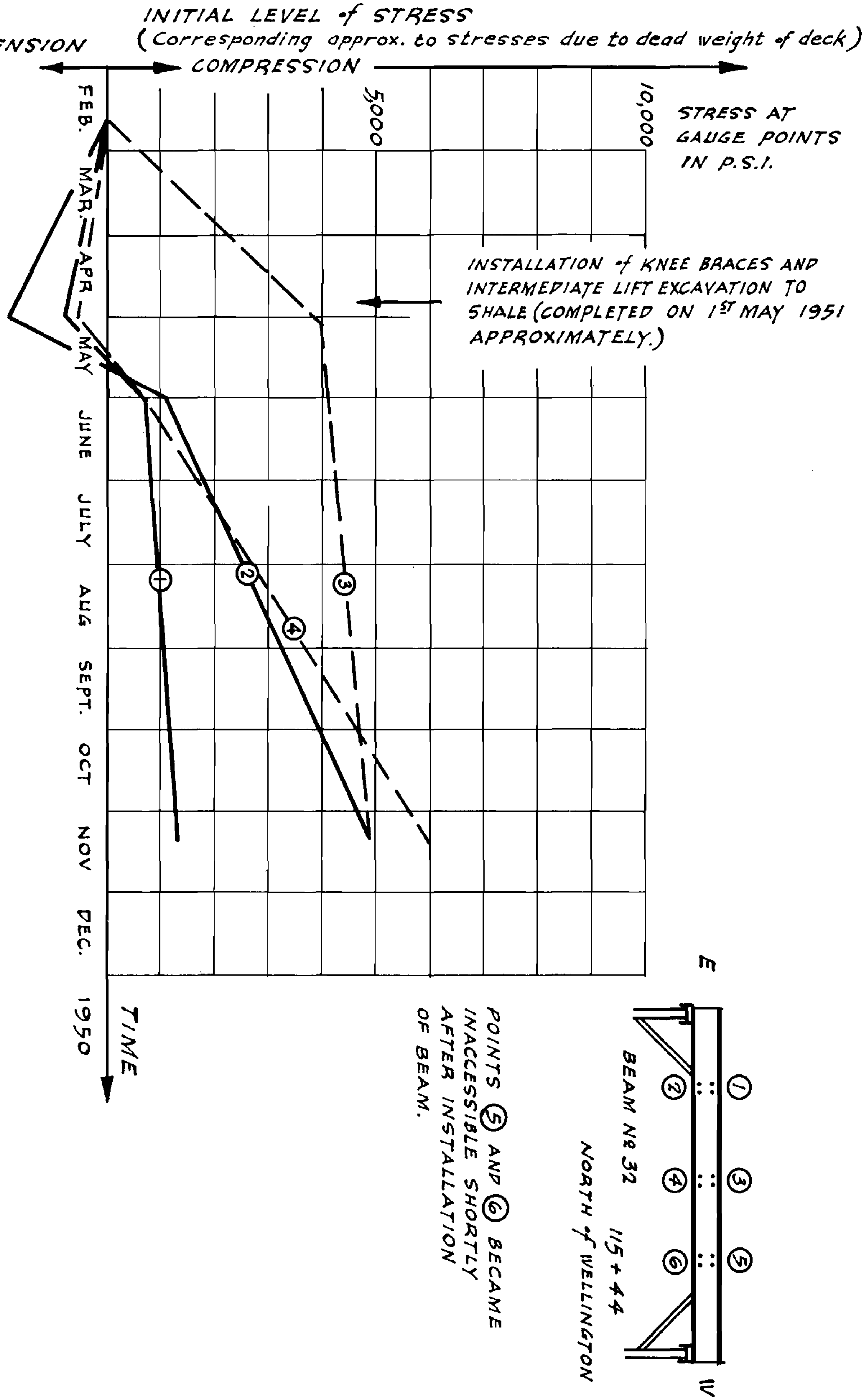


FIG. 20 EARTH PRESSURE STRESSES IN DECK BEAM

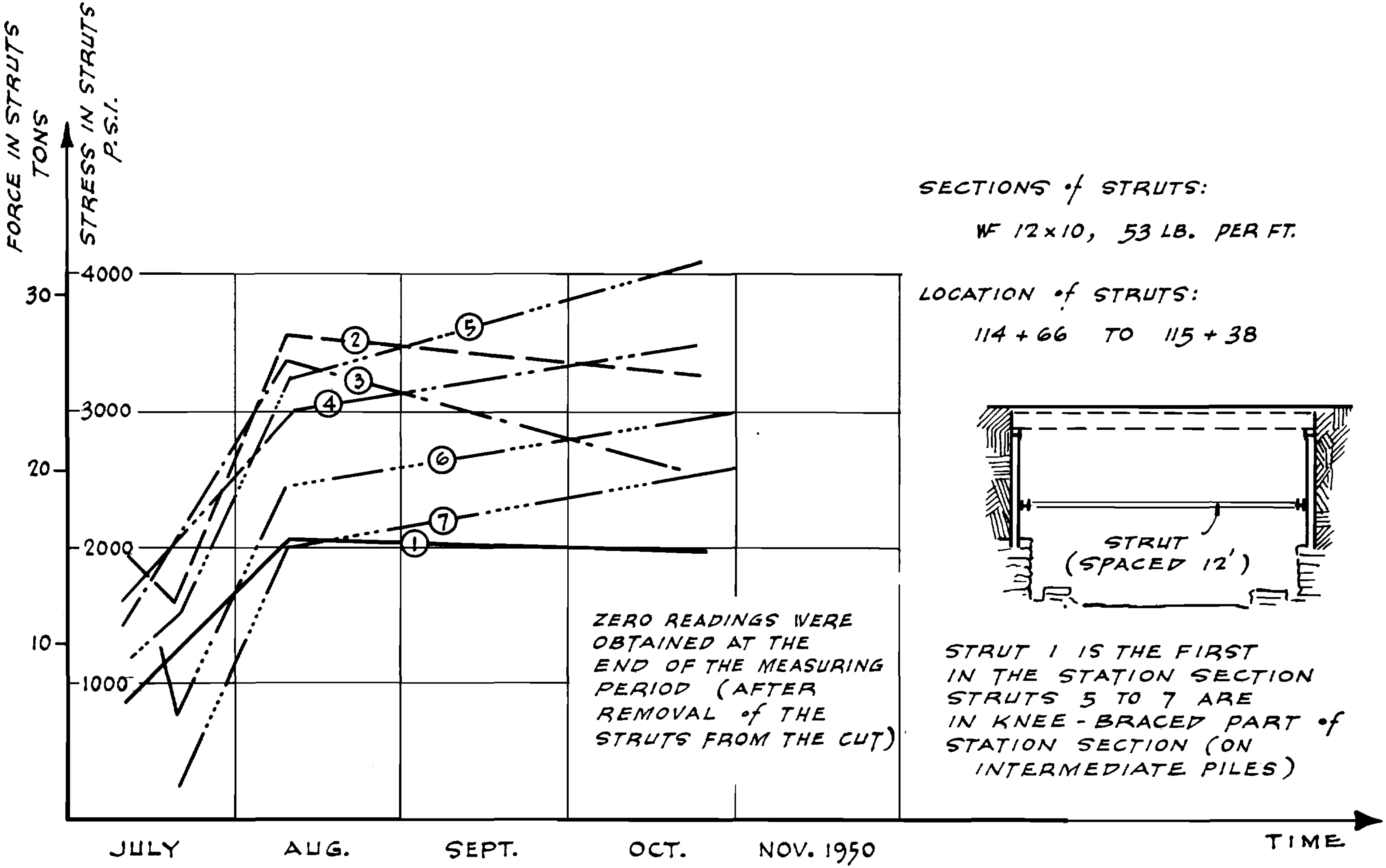


FIG. 21 EARTH PRESSURE MEASUREMENTS ON SEVEN STEEL STRUTS

T.N.B. SEPT. 1952