THE PERFORMANCE OF LAPPED SPLICES UNDER RAPID LOADING

By

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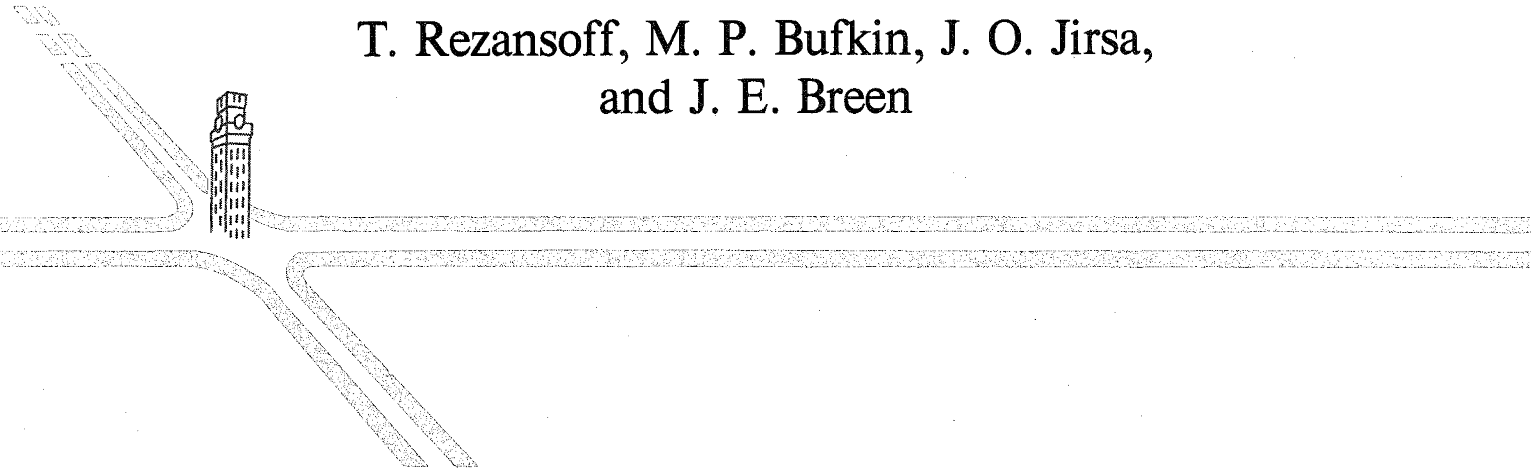

SUMMARY REPORT 154-2(S)

SUMMARY OF
RESEARCH REPORT 154-2

PROJECT 3-5-72-154

COOPERATIVE HIGHWAY RESEARCH PROGRAM
WITH TEXAS HIGHWAY DEPARTMENT
AND
U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN
JANUARY 1975

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Introduction

The impact or dynamic response and resistance of structures or structural components has been of increasing interest in recent years. Ground motions measured during the San Fernando earthquake [1] were more severe than previously considered possible and have resulted in a tightening of design provisions in seismic zones. The failures of lapped splices at the bases of some concrete highway support structures during the San Fernando earthquake lead to questions as to the suitability and adequacy of a lapped splice subjected to fast loading rates. Loadings produced by hurricanes and tornadoes or vehicular impact give impetus to the study of structural behavior under rapid loading.

In this investigation the behavior of lapped splices subjected to impact loading was studied. The objective was to compare the strength and behavior of splices under static and dynamic loads and to determine whether the design provisions based primarily on static tests could be relied on under dynamic loading conditions.

The investigation detailed herein represents one stage of a long-range study at The University of Texas at Austin into the behavior of lapped splices. The study includes experimental work to determine the influence of lap length, bar size, steel strength, bar spacing, concrete cover, moment gradient, and transverse reinforcement on the behavior of lapped splices [2]. In addition, an analysis of all available test data on splices and development lengths was carried out to provide a basis for developing improved design procedures [3].

Test Program

Two series of tests were conducted. In the first series, eight beams were tested to determine the influence of lap length on the strength and response of the beam. The specimens were subjected to impact loadings producing failure in either one cycle or in three to five cycles of incrementally increasing magnitude. The second series of tests included twelve beams. Four specimens contained 18 in. splices. Three were subjected to unidirectional cyclic impact loading. One was subjected to static loading. Eight beams had 30 in. splices and were subjected to either unidirectional or reversed cycles of impact loading. Load cycles were applied at a level less than that producing failure in one loading to destruction of the splice. Grade 60 reinforcement was used throughout the study. Concrete strengths ranged from 2.6 to 4.3 ksi. The results of four beams with lap splices, tested statically in a previous study [4], were used as a reference for static behavior.

Previous studies of specimens subjected to static loads have given considerable insight into the tensile splitting mechanism occurring during failure of a splice. This investigation concentrates on explaining differences between dynamic (impact) and static behavior of splices. The variation occurring in the material properties of steel and concrete subjected to different rates of loading is examined. The beam cross section and area of tensile reinforcing steel in the splice were the same throughout. Two-point symmetrical loading was applied to the simply supported beams to achieve a condition of constant moment and zero shear over the splice lap length. Analytical studies were carried out to help evaluate the experimental data and explain the higher mode response measured in the tests.

The Loading System

The system was designed to provide forces with variable peak levels for testing various lap length and stirrup arrangements used in the specimens, under both incrementally increasing and single impact load applications. To obtain load rates more typical of seismic or wind loading, it was necessary to alter the load pulse typical of an impact loading. By cushioning the impact, forces approximated a bilinear ramp with load maintained over a sufficient time to allow for maximum bending of an elastic specimen under the applied load level. Finally, a constant moment region over the splice was needed to eliminate the effects of shear on splice performance.

The loading system is illustrated by the schematic in Fig. 1. The main feature of the system was a falling mass which impacted the specimen through cushioning devices. The mass was raised to the chosen drop height using an overhead crane and a quick release hook (used for helicopter drop applications) was manually released. The total mass weight was 2600 lbs. Four steel pipes were used to guide the falling mass. The pipes were attached to the test

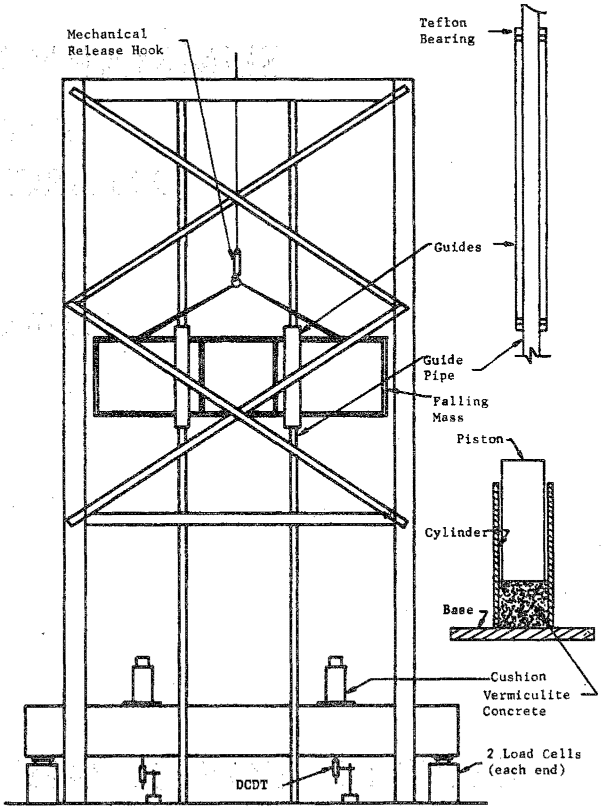

Fig. 1. Schematic of dynamic loading system.

floor and the top of a 20 ft. high braced steel frame.

Cushioning devices were used to provide an acceptable force-time relationship for the load pulses. Figure 1 illustrates the component parts of the cushioning devices. Vermiculite concrete cylinders were placed inside steel cylinders with closed bases that rested on the test specimen at the load points. Steel pistons which extended above the steel confining cylinders and rested on the vermiculite cushions received the direct impact of the falling mass. Compression of the vermiculite concrete between the specimen and the drop mass increased the rise time, reduced the peak force magnitude and extended the pulse time of the impact load on the specimen. Various combinations of the height of the vermiculite cylinders and diameters of the steel pistons were used to develop different load-time relationships.

The use of vermiculite concrete as a cushioning material was studied previously [5]. The consistency and workability of vermiculite concrete are very dependent on the water content. Energy absorbing characteristics of the vermiculite concrete are highly dependent on the air content. To obtain a uniform product, the mixing and casting techniques had to be standardized and extensive trial batching was carried out.

Test Procedure

Reactions, steel strains, and deflections were recorded on magnetic tape to give a continuous time history of the response for every load application. The rapid loading rate required the use of high speed tape recorders operating at 30 in. per second to record the data with sufficient resolution. Two 8-track FM tape recorders were used. One channel of each magnetic tape record was used to establish a common time reference signal, so that all data from both tapes could be referenced to the same instant in time.

Sample data traces are shown in Fig. 2 to illustrate typical behavior during an impact load application. Responses are drawn on the same horizontal time axis so that a vertical line intersects all curves at the same time. Recorded reactions display higher mode vibrations with a period of around 6 ms. Dashed lines show reaction curves which eliminate the higher modes. The vertical line labled "time instant for data analysis" identifies the time at which moments on the splice are at or near maximum values. Strains 1 and 2 are measured at the splice ends and indicate yielding. The rapid drop in strain 2 after reaching a peak is indicative of unloading following yield. Strain 6 is measured at the center of the lap splice where yielding does not occur because the tensile steel area is doubled and moments are the same as at the end of the splice. The smooth regular curve shown for the deflection at the west load point is typical. For the load cycle shown, the maximum deflection occurs later than the time at which maximum reactions are reached. For clarity, Fig. 2 does not show all the data recorded in the test indicated.

Theoretical Analysis

A theoretical study was undertaken to determine if the measured dynamic response could be reasonably simulated analytically. The model of the concrete beam was assumed to behave elastically. The analysis was carried out using a finite (central) difference time marching algorithm for an undamped multi-degree of freedom lumped mass system. The time range over which the dynamic behavior was investigated was generally less than one period of the natural vibration of the first (fundamental) mode, and long time effects of damping were of no concern. The rotational inertia effects neglected by a lumped mass representation were of no consequence when short beam segments were used to discretize the model.

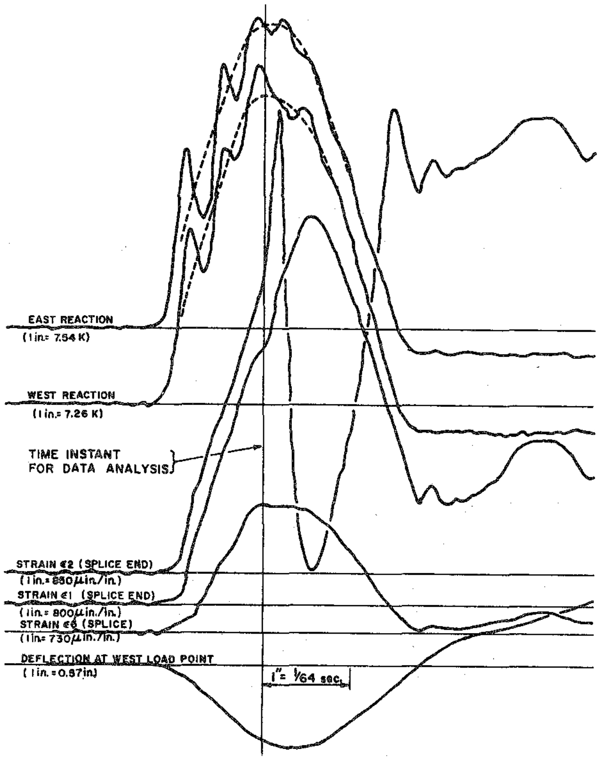

Fig. 2. Measured response for Specimen C-30-2T, load cycle 1, drop height =18 in.

A parametric study was undertaken to define relationships between forces, reactions, moments, and deflections under dynamic loading. Since the variation of applied forces and beam properties may be quite large, a trial and error procedure was used to vary the parameters. The parametric study was also used to explain specific response patterns which were recorded experimentally. The insight gained by studying the predicted response was invaluable in evaluating the observed response.

The parametric study explored in detail variations in the load or forcing function, beam stiffness, and drop mass, which could account for some of the responses observed in the test program. General response patterns from the experimental program were duplicated in the theoretical study. It was shown that the higher mode vibration effects could be eliminated in examining the test data. The maximum moment along the splice was closely approximated by multiplying the maximum reaction by the shear span of the beam. The exact shape of the forcing functions did not appear to influence significantly the response of the beam. Complete details of the theoretical analysis are contained in Ref. 6.

Evaluation of Capacity of a Lap Splice under Impact Loads

To compare static and dynamic behavior of lap splices, it is necessary to compare maximum strengths reached under both loading methods. Since higher capacities were always found under impact loading, strain rates were examined to determine effects on material characteristics.

The observation of dynamic splice strengths well above the static strengths gave impetus to determining the effects of high strain rates on the properties of the reinforcing steel and the concrete. Therefore, it was necessary to obtain reasonably accurate rates of strain for both the steel and concrete from which estimates of the material strengths and resulting specimen strengths could be made. Studies by Flathau [7] and Feldman, et al. [8] on reinforcing steel indicate that yield strength might be expected to increase from 15 to 40 percent for strain rates varying from 0.1 to 0.3 in./in./sec. as measured in the splice tests.

The concrete tensile splitting stresses which develop in the splice region must reflect the steel stress rates observed. However, the rate at which different sections along the splice are being stressed in tension cannot be determined, but estimates of the rates of the average splitting tensile stresses in the concrete can be made for the maximum loads and moments attained in a given load cycle and indicate a stress rate of about 24000 psi/sec. Galloway and Raithby [9] studied the effect of high stress rates (comparable to the ones used in the current investigation) on the modulus of rupture of plain concrete. The modulus of rupture can be assumed a reasonable indicator of the tensile splitting resistance of the concrete. These tests indicate that increases in tensile splitting resistance at high stress rates could accommodate the expected increases in yield strength.

Summary and Design Implications

For dynamic loads with strain rates as investigated in the study, moments acting on the splice with magnitudes equal to the static capacity can be carried over many applications of unidirectional or reversed impact loading without deterioration leading to failure. When dynamic moments exceeding the static moment capacity are applied, the maximum splice capacity is dependent on the rate of loading. The load rate establishes the dynamic yield stress of the steel and the dynamic tensile strength of the concrete. Either the concrete or the steel can limit the dynamic moment carried by the splice.

Evaluation of dynamic splice performance where the splice is loaded above the static capacity must consider toughness and durability characteristics. Parameters influencing the toughness and durability evaluations include the type of loading (unidirectional versus reversal, and large impact versus small impact), and the presence of stirrups along the splice.

Specimens were able to carry many cycles of loading prior to a splice failure if small drop heights were used so that moments did not significantly exceed the static moment capacity (say 5 to 10 percent over static moment). With very large drop heights, the dynamic moments were 40 to 50 percent (30 in. splices) or 70 to 75 percent (18 in. splices) above the static capacity, but splice failure resulted after very few cycles of loading.

Reversed loading appeared to be no worse than unidirectional loading. For similar specimens, smaller reactions and splice moments were induced for reversed loading with the same drop height because energy was absorbed in overcoming the inelastic residual deformation.

As expected, the placement of stirrups along the splice greatly enhanced all toughness and durability characteristics of the splice. Dynamic loads were sustained with total deflections of at least twice the deflections found in similar specimens without splice stirrups.

In general, the dynamic moment capacity of a splice is at least as large and usually larger than the static moment capacity. Dynamic splice moments as large as the static capacity were safely carried for loading rates that induced steel strain rates as high as 0.3 in./in./sec. Therefore, a splice length based on design specifications developed using static test results would appear to provide adequate capacity under dynamic loading conditions provided shear was minimal in the splice region.

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KEY WORDS: lapped splices, rapid loading, static, dynamic, strength, behavior.

The full text of Research Report 154-2 can be obtained from Mr. Phillip L. Wilson, State Planning Engineer, Planning & Research Division, File D-10, State Department of Highways and Public Transportation, P. O. Box 5051, Austin, Texas 78763.