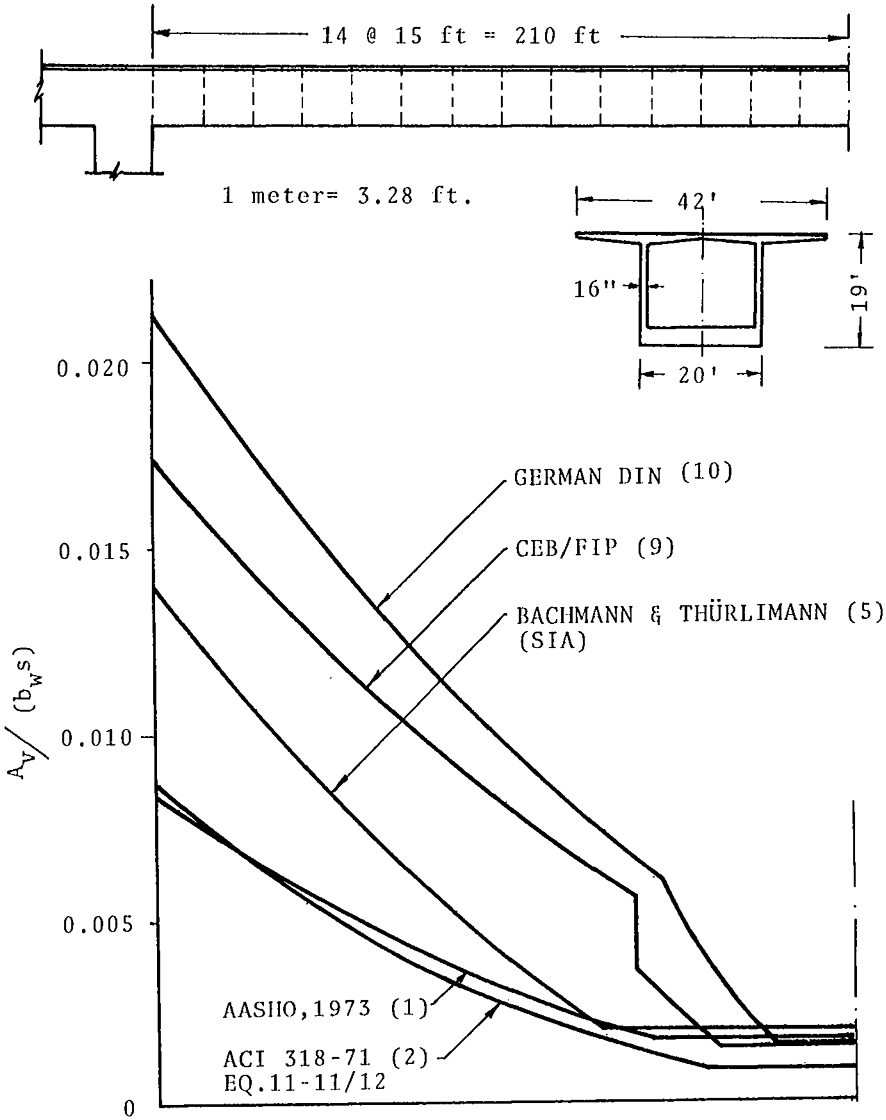

FIG.1 REQUIRED SHEAR REINFORCEMENT IN DIFFERENT CODES

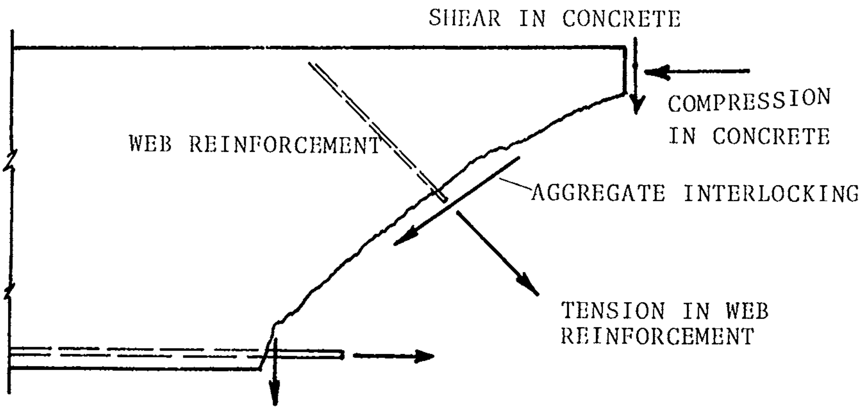

FIG.2 FORCES AT CRITICAL CRACK

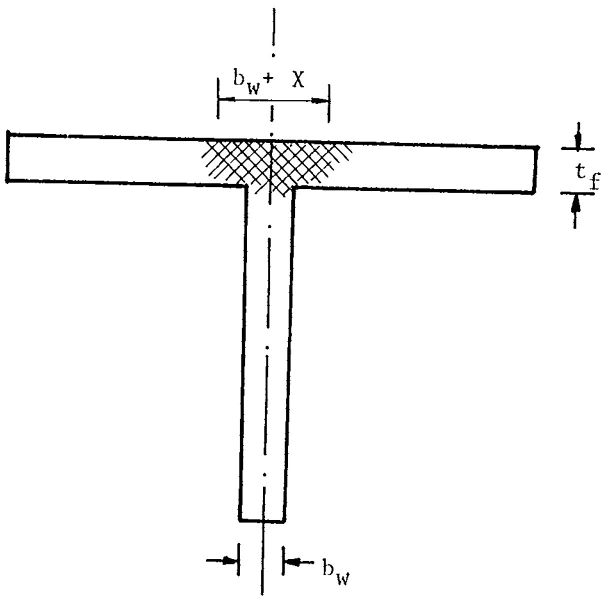

FIG.3 EFFECTIVE FLANGE WIDTH FOR SHEAR TRANSFER

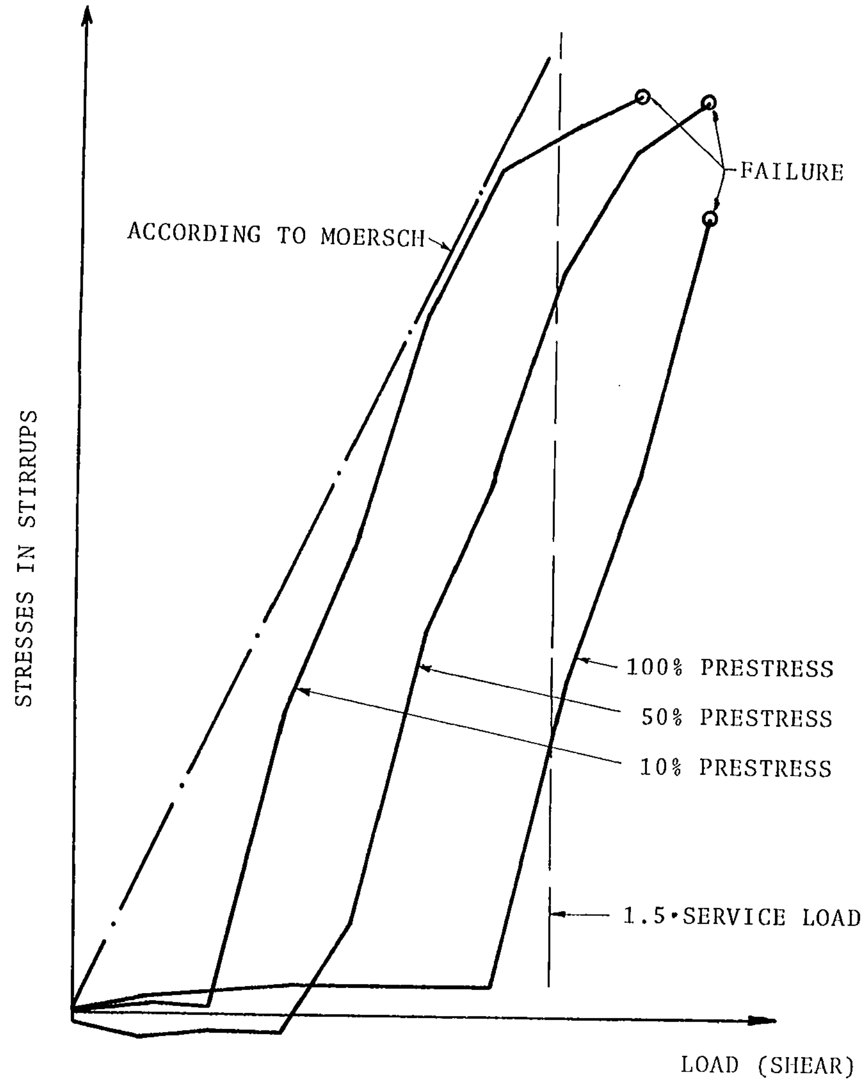

FIG.4 STRESS OF WEB REINFORCEMENT IN BEAMS WITH DIFFERENT DEGREE OF PRESTRESS Leonhardt(21)

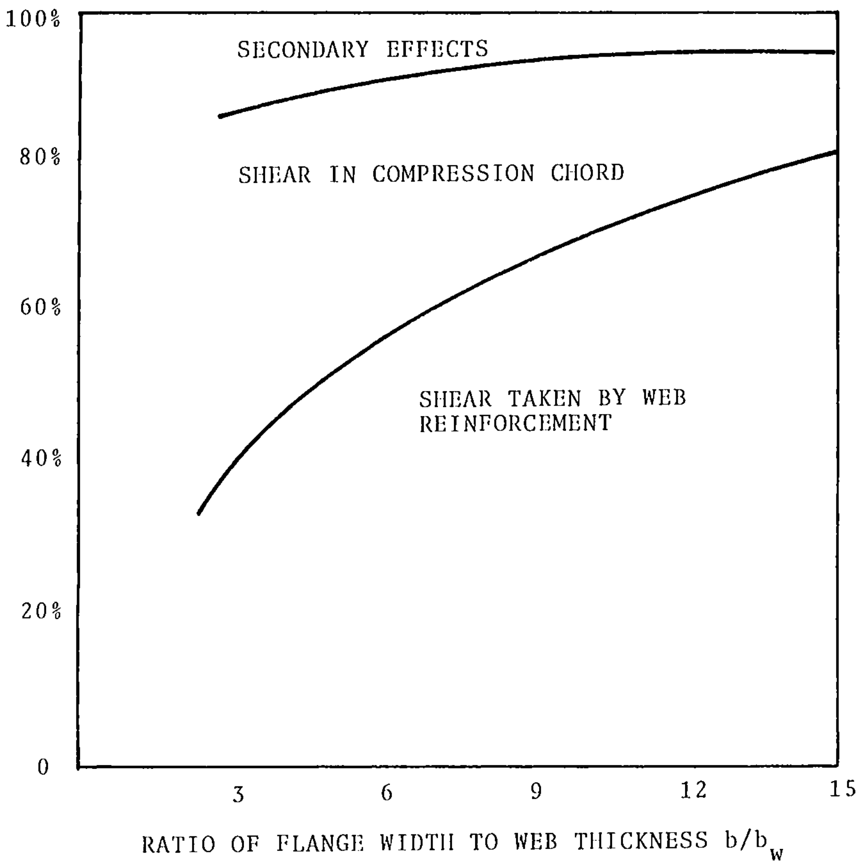

FIG.5 DISTRIBUTION OF SHEAR FORCE, Leonhardt (19)

SP 42-15

Dynamic Shear Strength Of Reinforced Concrete Beams

By
R. H. Seabold

Synopsis: Theoretical and experimental work was done to study shear and diagonal tension in reinforced concrete beams for protective construction against the blast effects of nuclear and conventional weapons. Criteria were determined for the minimum amount of web reinforcement required for developing the ultimate flexural resistance of beams subjected to dynamic loading. Rigorous and simplified analysis methods and a simplified design method were developed, and 53 beams were tested. The rigorous method was found to predict behavior up to the usable ultimate shear strength within normal engineering accuracy, and to provide a fair estimate of the time, location, and mode of failure. Provisions for the dynamic loading case were expressed in notation and format similar to that of the ACI Code to provide practical guidance for designers.

Keywords: beams (supports); bonding; building codes; computer programs; diagonal tension; dynamic loads; failure; modulus of elasticity; reinforced concrete; research; shear strength; shear tests; structural analysis; structural design; web reinforcement.

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INTRODUCTION

Objectives

Theoretical and experimental work was done at the Naval Civil Engineering Laboratory to study shear and diagonal tension in reinforced concrete beams for protective construction against the blast effects of nuclear and conventional weapons. The work was sponsored by the Defense Nuclear Agency (formerly the Defense Atomic Support Agency).

Primary objectives of the work were to determine criteria for the minimum amount of web reinforcement required for developing the ultimate flexural resistance of beams, and to determine the difference between these criteria for static and dynamic loading. Secondary objectives were to develop methods and equations with confidence limits consistent with those associated with flexure, and to present the results in a simple, yet complete, form to provide practical guidance for designers.

Scope

The scope of this paper is limited to a presentation of some of the results of the work. Emphasis is placed on recommended equations and design criteria, and how they are expressed in notation and format similar to the ACI Code to provide practical design guidance.

In keeping with ACI publication policy, the text is written for "those who wish to know only the facts uncovered and the conclusions reached." A technical report (1) covering all of the work has been published by the Naval Civil Engineering Laboratory and is recommended for "those who in addition want to review the details of the investigation which uncovered those facts and all of the data on which the conclusions are based."

In keeping with the objectives of this symposium, the text is addressed to a designer in the form of a 20-minute formal speech on the session theme, which is practical design applications. Appendix A contains details not presented in the speech, but suggested by the reviewers to improve the paper.

Background

Most of the work was limited to rectangular, reinforced concrete beams on simple supports and subjected to uniformly distributed dynamic and static loads.

The main portion of the experimental work consisted of testing 53 beams; 29 were loaded dynamically and 24 were loaded statically. Emphasis was placed on effectiveness of web reinforcement; 47 beams contained web reinforcement and six had none. The beams were full size and about 12 feet long. All of the beams were rectangular except 10 that were I-shaped, and all were slender except five of the I-shaped beams that were of intermediate slenderness. A ratio of span length and effective depth between five and seven was considered to be intermediate slenderness.

All of the beams were tested in the blast simulator at the Naval Civil Engineering Laboratory. Static loads were applied using compressed air, and dynamic loads were applied using the expanding gas from detonation of Primacord explosive. Twenty-eight channels of electronic instrumentation were used in each beam test to make continuous measurements of loads, reactions, accelerations, deflections, and strains. Strains were measured in the stirrups, the longitudinal tension and compression steel, and the remote fiber of the concrete at various positions along the span.

In addition, tests were conducted on material samples to determine dynamic strengths of materials, including the steel in tension and the concrete in both tension and compression.

A simplified design method and both simplified and rigorous analysis methods were developed for simply supported rectangular, reinforced concrete beams under uniform and concentrated dynamic loads. Many of the equations apply to other conditions of loading and restraint as well. Equations were developed for predicting the maximum dynamic shear at the support (used in the simplified methods); the shear at the support with respect to time (used in the rigorous method); and the dynamic resistance of the beam at the support corresponding to shear cracking, shear yielding, shear failure, flexural yielding, and flexural failure.

A computer code was programmed to make calculations using the rigorous method. The procedure is based on the linear acceleration extrapolation method for numerical analysis of single-degree-of-freedom systems; for each cycle of the calculation, checks are made for shear and bond. The procedure applies in the elastic, elasto-plastic, and plastic regions of response, and the motion parameters (displacement, velocity, and acceleration) are calculated for each cycle; therefore, the procedure applies to all sequences of yielding and all modes of failure.

The theory includes a concept of ductility along the span at the shear-compression zone as well as at the critical flexural section. It also includes effects of beam motion on the strain rates and dynamic yield strengths of materials, effects of beam motion on moment of inertia and spring constant (which is actually a variable), and inelastic hinging.

The rigorous method was found to predict behavior up to the usable ultimate shear strength within normal engineering accuracy, and to provide a fair estimate of the time, location, and mode of failure. In the case of beams designed to remain elastic, a capacity reduction factor of 0.85 in shear was sufficient to insure against yielding in shear due to uncertainties in the method and in the fabrication of beams. In the case of beams designed to respond in the inelastic regime, a capacity reduction factor of unity in both shear and flexure is sufficient to insure against yielding of stirrups prior to yielding in flexure and yielding of the shear-compression zone prior to failure in flexure. Greater uncertainties in shear in the simplified methods make it necessary to use capacity reduction factors of 0.75 (elastic) and 0.90 (inelastic) to insure development of the desired flexural resistance and maintain ductility along the span.

NOTATION

Discussion

ACI notation was used insofar as practical, but additional symbols, subscripts, and superscripts were introduced to provide more precise designation. In general, uppercase letters indicate forces while lowercase letters indicate forces per unit area. Where it is necessary to indicate location at the support rather than at the critical section, the subscript s is used to specify location at the support. A letter d is added to the subscripts of symbols to denote the dynamic case. It was necessary to differentiate between the strengths of stirrups and longitudinal tension and compression steel; therefore, the subscript contains a letter v to denote stirrup material, and a prime denotes a material in compression.

The work was completed in 1970 and therefore does not include the changes in notation adopted by ACI in 1971.

Symbols

The list of symbols given at the end of this paper is a complete list of those in the paper. It is only a partial list of those in the Naval Civil Engineering Laboratory report (1), and a few symbols have been changed to conform to the notation adopted by ACI in 1971.

The following symbols are a departure from ordinary ACI usage, but were necessary to differentiate among stresses in different steels:

f_{vy} Static yield strength of stirrups (psi)

f_y Static yield strength of tension bars (psi)

f'_y Static yield strength of compression bars (psi)

DEFINITIONS

Critical Strains

There is insufficient time to observe deflections or the formation of cracks in order to make judgments regarding change in behavior during dynamic tests; measured values instead of visual observations must be used. Therefore, it is necessary to define changes in behavior such as cracking, yielding, and failure in quantitative terms. These quantities should be easily measured in tests, should apply in the inelastic as well as the elastic regime, and should be applied to both the static and dynamic cases in order to make valid comparisons. Thus, all changes in behavior were defined in terms of critical strains.

Traditional practice of using stress criteria in static design did not cause a serious problem, because the modulus of elasticity of steel does not change an appreciable amount as the strain rate is increased, and the modulus of elasticity of concrete increases by only a small amount. Unless determined otherwise in tests, the modulus of elasticity for steel in the dynamic and static cases can be assumed to be

$$E_s = 29{,}000{,}000 \text{ psi} \tag{1}$$

Unless determined otherwise in tests, the modulus of elasticity for concrete in compression in the dynamic and static cases can be assumed to be

$$E_c = w^{1.5}\, 33\sqrt{f'_c} \tag{2}$$

In the computer code of the rigorous method, the increase in concrete modulus was considered by using the dynamic compressive strength of the concrete in place of the static strength in Equation 2. For the simplified methods, the equation was used as shown. The magnitude of the net effect of the increase in modulus in beams is probably less than the total error due to other uncertainties such as possible changes in stress block shape, approximation of the static modulus, etc.

Yield strength, yield strain, ultimate strength, and ultimate strain of concrete in compression are not well defined due to the nonlinear stress-strain relationship, and also due to differences in behavior between concrete constrained by reinforcement in beams and unconstrained concrete in test cylinders. However, when combining concrete and steel to form beams, it becomes necessary to establish effective values of these properties for proportioning the beams and defining the regions of response. Under dynamic loading, the percent increase in yield strain is less than the percent increase in yield stress, and the increase in ultimate strain in beams is unknown. Critical events of concrete behavior in compression for both the dynamic and static cases were defined as strains in quantitative terms as follows:

Static and dynamic yield strain of concrete:

$$\varepsilon_{cy} = 0.003 \text{ in./in.} \tag{3}$$

Static and dynamic ultimate strain of concrete:

$$\varepsilon_{cu} = 0.006 \text{ in./in.} \tag{4}$$

Stresses associated with the critical strains were defined as follows:

Static yield strength of concrete:

$$f_{cy} = 0.85\, f'_c \tag{5}$$

Dynamic yield strength of concrete:

$$f_{dcy} = 0.85\, f'_{dc} \tag{6}$$

Static ultimate strength of concrete:

$$f_{cu} = f'_c \tag{7}$$

Dynamic ultimate strength of concrete:

$$f_{dcu} = f'_{dc} \tag{8}$$

Other compressive stresses in the concrete in the various regions of response were computed as follows:

Static loading, elastic region ($\varepsilon_c \leq \varepsilon_{cy}$):

$$f_c = \varepsilon_c E_c \leq f_{cy} \tag{9}$$

Dynamic loading, elastic region ($\varepsilon_c \leq \varepsilon_{cy}$):

$$f_c = \varepsilon_c E_c \leq f_{dcy} \tag{10}$$

Static loading, inelastic region ($\varepsilon_{cy} < \varepsilon_c \leq \varepsilon_{cu}$):

$$f_{cy} < f_c = \varepsilon_c E_c \leq f_{cu} \tag{11}$$

Dynamic loading, inelastic region ($\varepsilon_{cy} < \varepsilon_c \leq \varepsilon_{cu}$):

$$f_{dcy} < f_c = \varepsilon_c E_c \leq f_{dcu} \tag{12}$$

These precise rules (Equations 9 through 12) were very important, because the stress, strain, yield stress, ultimate stress, and modulus are time dependent for dynamic loading.

Flexure

Flexural cracking of the beam occurs when the tensile strength of the concrete is overcome at sections where bending forces are paramount and shear cracks do not already exist. In the accepted