Composite Beams of Steel and Lightweight Concrete

IRWIN A. BENJAMIN

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SINCE PUBLICATION of the 1961 AISC Specification, interest in composite design has grown. Concurrent with this growth in interest has been the development of new types of shear connectors and the use of composite design with lightweight concrete floor slabs.

Data from tests on lightweight aggregate concrete composite beams was not available in 1961 when the current AISC Specification was developed. Since that time tests have been run on beams with lightweight concrete, with satisfactory results. This paper has a two-fold purpose: to discuss a general method of evaluating composite beam tests, and to review the data on the effectiveness of shear connectors in lightweight concrete composite beams.

LIGHTWEIGHT AGGREGATE CONCRETE

Lightweight concrete differs from concrete made with the normal aggregate[1] permitted by Section 1.11 of the AISC Specification. Lightweight concrete has advantages of greater fire resistance and reduced dead load weight in the structure. It also has disadvantages, having a reduced modulus of elasticity and, in some cases, greater shrinkage and creep properties. Lightweight concrete is a generic term which is not very descriptive, since the properties of lightweight concretes vary considerably. Figure 1 shows shrinkage and creep data, compiled from Bureau of Standards Monograph No. 74,[2] for a series of lightweight and regular weight concretes. The wide range in creep properties of lightweight concretes is evident. Also, the graph shows that some of the lightweight concretes actually have lower shrinkage and creep than some of the regular weight concretes.

The physical properties of concretes made with any generic type of aggregate will vary over a wide spectrum. However, the basic question is not whether the properties of concretes are different or varied, but rather, whether lightweight concrete can be effectively used to design composite beams.

Irwin A. Benjamin is Director of Research, Granco Steel Products Co., St. Louis, Mo.

COMPOSITE DESIGN ASSUMPTIONS

The philosophy of composite design in the AISC Specification is predicated on three assumptions:

1. The ultimate load capacity of the shear connector is not exceeded when the beam has reached its ultimate moment capacity.
2. At the ultimate moment capacity of the beam, if the shear connection is sufficient, a rectangular stress block is developed in the steel beam with the steel section substantially at yield strength over its full depth.
3. Uniform spacing of connectors may be used from point of maximum moment to the support.

Full scale beam tests will determine whether a new type connector or a different type of concrete will satisfy these design assumptions. Such beam tests should answer the following questions:

1. Will deflections of the test beam agree with the theoretical composite model?
2. What is the character of the stress block developed as ultimate moment capacity is approached?
3. Will the location of the neutral axis agree with theoretical calculations both in the elastic and plastic range of stress?
4. Will the ultimate moment capacity of the beam be developed?

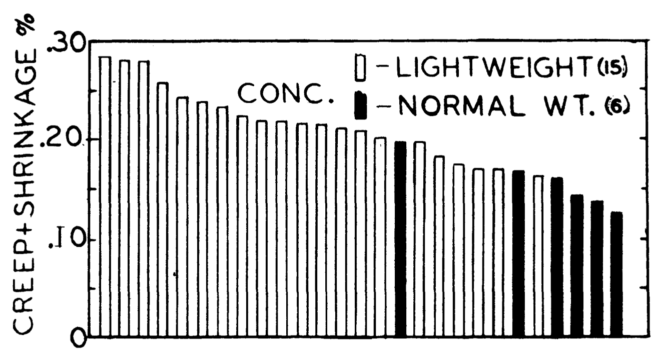

Figure 1

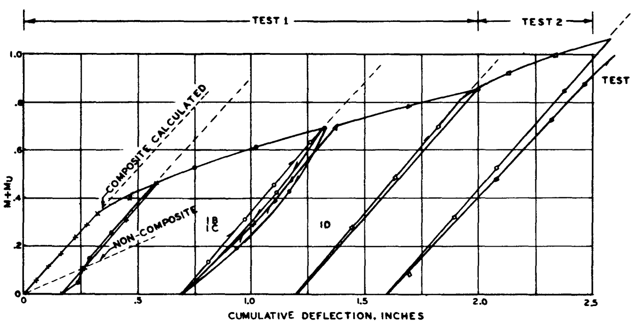

Figure 2

Deflections—The theoretical load-deflection curve can be accurately predicted by taking into account both the flexural and shear deformations of the beam. The load deflection data from a series of tests in which a lightweight concrete composite beam was loaded and unloaded at approximately 0.4, 0.6, 0.8 and 1.0 times the ultimate moment capacity is shown in Fig. 2. The theoretical deflection is shown as a dotted line for both the composite and non-composite sections. The beam followed the theoretical deflection curve even after loading and unloading at the calculated ultimate moment capacity, indicating that the beam with lightweight concrete stayed composite under repeated loading in the plastic range.

The designing engineer is interested in the recovery of the beam after loading. Figure 3 shows the percent of recovery for a series of lightweight and regular weight concrete beams loaded to two-thirds of the yield point of the beam, approximately the design load range. Note that there is no significant difference in the percent recovery of the beams with the two types of concrete.

The Stress Block—The theory of composite design is based on the assumption that the stress distribution in the beam will, at ultimate moment, approximate the rectangular stress block shown in Fig. 4. This distribution requires the beam to be at yield throughout its cross

Deflection Recovery for Eight Composite Beam Tests

Type of Connector	Percent Recovery[a]	
	Lt. Wt. Concrete	Regular Concrete
7/8 in. stud	98	. .
5/8 in. stud	95	96
1/2 in. stud	. .	95
4 in. channel	97	96

[a] Recovery after loading to two-thirds of yield stress of steel beam.

Figure 3

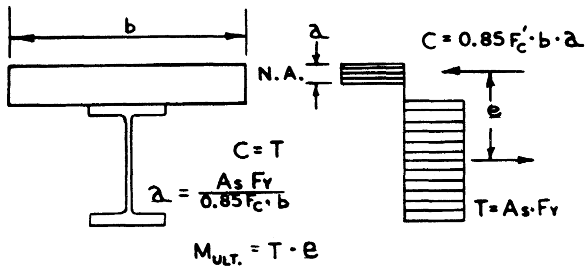

Figure 4

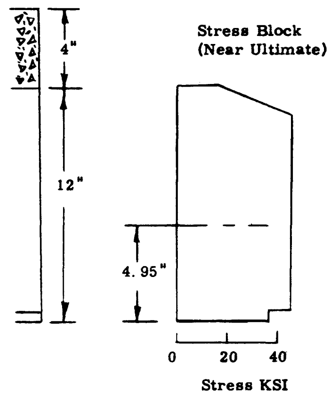

Figure 5

section. The actual measured stresses on a beam using lightweight concrete are shown in Fig. 5. These stresses closely approximate the assumption of a rectangular stress block. From this data it can be concluded that the stress in the steel beam validates our design and that the shear connection was effective in the lightweight concrete.

With the stress block fully developed as shown here, the load on the shear connectors can be simply calculated from the total tension developed in the steel beam, as given in Formula 19 of Section 1.11 of the AISC Specification.

The Neutral Axis—In many respects the movement of the neutral axis is the best indicator of the performance of the composite beam. The neutral axis can be accurately located by means of strain gages placed on a vertical section. The measured and theoretical location of the neutral axis in both elastic range and at ultimate moment should closely agree, if adequate composite action is developed.

In the elastic range stress distribution is considered to be triangular in both the concrete and steel. As ultimate moment capacity is approached, the distribution in the concrete changes from a triangular to a rectangular stress block; consequently the neutral axis,

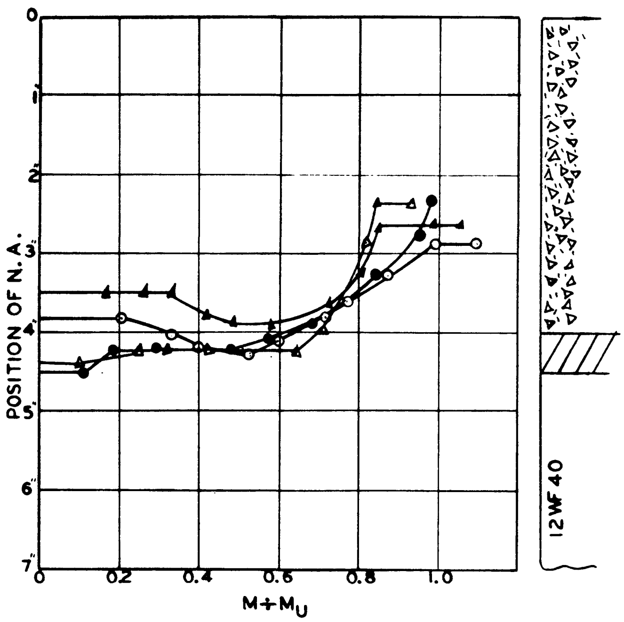

Figure 6

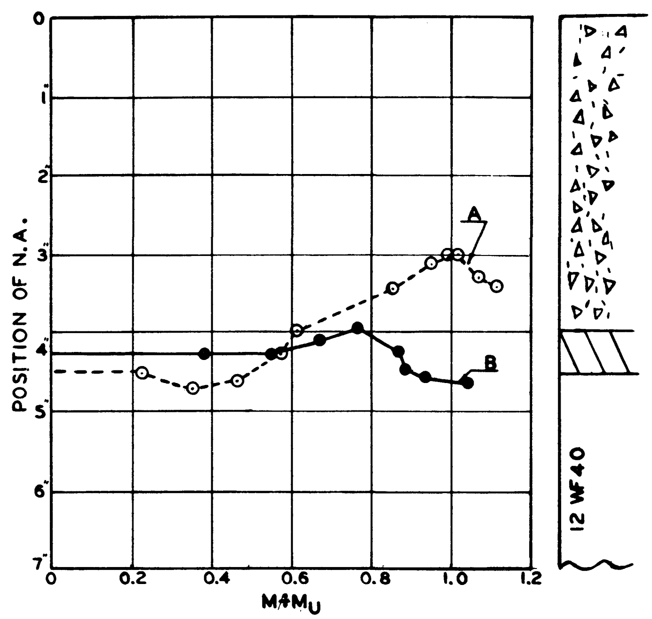

Figure 8

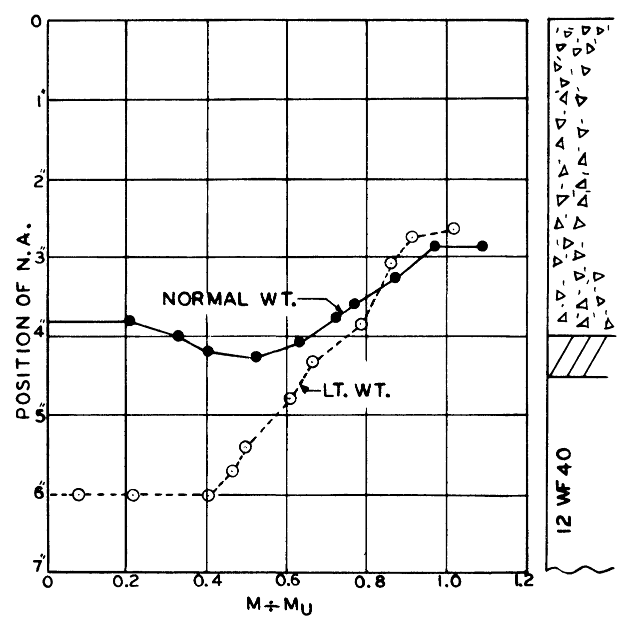

Figure 7

the bottom of the stress block, must rise. The change in neutral axis as the beam approaches ultimate load is shown in Fig. 6 for a group of regular weight concrete beams. On the beams shown, at a moment of about 0.6 of the calculated ultimate moment, the neutral axis starts rising and continues to do so until the concrete stress block becomes rectangular.

The modulus of elasticity for lightweight concrete is about 55 percent that of regular weight concrete of the same strength. Therefore, in the elastic range more lightweight concrete is required to balance the steel area, or the neutral axis will be lower in the beam. As the beam approaches its ultimate moment capacity and the concrete is in the plastic range, the neutral axis location is independent of the modulus of elasticity, as indicated in Fig. 4.

Beams with either type of concrete should have their neutral axis at ultimate moment at the same level for comparable strengths of concrete. Figure 7 shows the lower elevation of the neutral axis in the elastic range for the lightweight concrete beam; however, both beams have the same location of the neutral axis at ultimate moment. This type of graph verifies that the ultimate moment theory, as given in Formula 19 of the AISC Specification, could also be valid for lightweight concrete.

The movement of the neutral axis in a beam with inadequate shear connection is shown in Fig. 8. On these beams the loss in effective composite action is indicated by a downward movement of the neutral axis. The loss is indicated at about 0.8 of the calculated ultimate moment for beam B; and at ultimate moment for beam A. Although the particular test may have developed the calculated ultimate moment capacity, the reversal is an indication of progressive loss of composite action with increase in load. Since design under the AISC Specification is predicated on the shear connector having a reserve strength 25 per cent greater than that required to develop the beam, the connection shown would be inadequate. This data points out the fallacy of evaluating the beam performance solely on the development of the ultimate moment capacity.

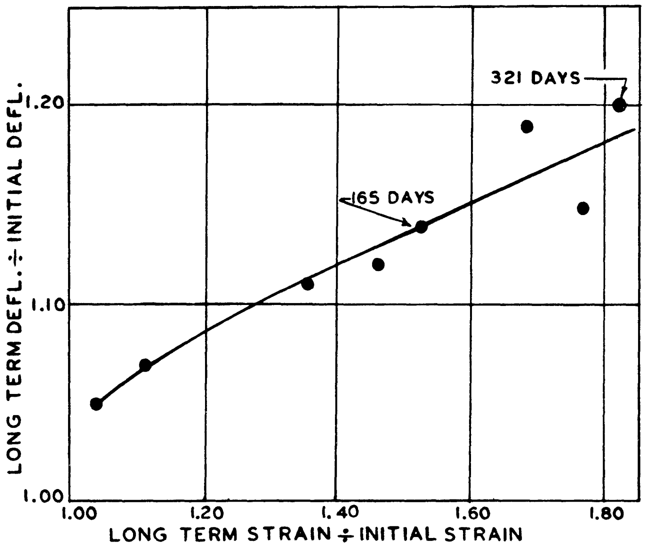

Figure 9

Ultimate Moment—The ultimate moment capacity of the beam, based upon the yield strength of the beam and the compression strength of the concrete, can be calculated as shown in Fig. 4. The calculation can be further refined by taking into account the difference in yield strengths of the web and flanges, which consistently occurs on rolled structural sections. On a properly designed composite beam the shear connectors should develop the calculated ultimate moment capacity. The development of ultimate moment capacity by itself is only one criterion. Loss of fully effective composite action can occur, yet a particular test beam can develop the ultimate moment capacity by strain hardening of the bottom flange.

Evaluation—The above four criteria—deflections, stress block, neutral axis, and ultimate moment, when considered together, serve to evaluate the performance of a composite beam. These criteria can be used to evaluate different types of concrete or new types of shear connectors for composite beams.

PLASTIC FLOW

When discussing lightweight concrete composite beams a question is often raised regarding the effect of plastic flow on the composite action. Plastic flow in a composite steel-concrete beam will be far less than that in a comparable size T-beam made entirely of concrete. The steel part of the composite beam does not flow; therefore only a portion of the overall beam is subject to readjustment due to creep.

Plastic flow data for a beam which had been under full load for almost a year is shown in Fig. 9. This beam is composite and designed with lightweight concrete, on a 25 ft span with simple supports, and is loaded to design stress. The data indicates that although the plastic flow as measured by the concrete strains increased about 80 percent over the initial strain, only a 20 percent increase in deflection was measured.

SUMMARY

A method of evaluation of tests on composite beams has been presented. This method, which may be applied to any composite beam, has been presented in conjunction with data on lightweight concrete beams.

The composite beams reported here, made with lightweight aggregate concretes, have been shown to satisfy the following requirements:

Development of the predicted deflections.
Development of the theoretical stress block.
An upward movement of the neutral axis as the beam approaches failure.
Sufficient shear connection to develop the ultimate capacity of the beam.

REFERENCES

1. Standard Specifications for Concrete Aggregates, *ASTM Designation C33.*
2. *Reichard, T. W.* Creep and Drying Shrinkage of Lightweight and Normal Weight Concretes, *NBS Monograph No. 74, March 1964.*
3. Evaluation of the Shear Connector, *Granco Research Department Report T-1045SR.*
4. Composite Beam under Prolonged Load, *Granco Research Department Report T-1178.*
5. *Sweeney, G. M.* Load-Deformation Behavior of Composite Bridge Stringers, *M.S. Thesis, University of Missouri.*