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TESTS AND ANALYSIS FOR COMPOSITE ACTION IN GLULAM BRIDGE SYSTEMS

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ABSTRACT

Rural transportation systems are of major importance to the nation's economy and to its ability to maintain a position of preeminence in the production of food and fiber. Safety of rural bridges in many cases has deteriorated to a dangerous level rendering many avenues for the movement of goods and people to an unusable state. The recently developed glulam bridge system, composed of laminated stringers and deck fastened together by bolted and doweled connections, offers great potential in needed national bridge replacement programs. This system used aesthetically pleasing, low energy materials and offers economy, quick erection and long service life.

In the fall of 1975, an interdisciplinary team of researchers was organized at Colorado State University under the sponsorship of the Engineering Foundation and the American Institute of Timber Construction to investigate the potential for composite action in glulam bridge systems. The goal of developing an appropriate mathematical model for the static behavior of the system was realized through theoretical and experimental studies of reduced-scale double T-beams which modeled glulam bridge cross-sections. Results, to date, have shown that recognition and quantitative evaluation of the composite action in glulam bridges is feasible for full-size bridges. Theoretically composite design can result in up to as much as 50% reduction in deflection as opposed to current design procedures which neglect this component interaction. Design improvements could lead to even greater amounts of increased stiffness as well as increased strength. Suggestions for future research are directed at further quantification of design methods which must include wheel load distributions along with influences of repetitive loading and other variables which typify real bridge loadings.

1. MOTIVATION FOR THE STUDY

Rural transportation avenues are major byways for the movement of meat, poultry, agricultural goods and many other consumer products. As a consequence of almost sole emphasis on our Interstate System, nearly 95% of the bridges on rural roadways, and many of our forest and mining roads are of pre-1935 vintage. In many cases these bridges are inadequate for present day demands or have deteriorated seriously. Failure to replace and maintain these bridges will severely hamper the transportation of and, consequently, the level of production of farm goods and many raw materials. A significant percentage of bridges on rural school bus routes have outdated design and/or configuration or have badly deteriorated so as to render them unsafe. In fact, newspaper accounts in some states have labeled them "death traps". These facts, combined with continued abandonment of rail service to rural areas, make bridge replacement programs a vital and urgent need of this country.

A new timber bridge configuration, comprised of preservatively treated glued-laminated (glulam) stringers and novel glulam deck panels, has been recently developed and achieves a modern, practical timber bridge system. Today, these bridges are increasing in popularity due to their low material cost, ease of erection, and natural beauty. The use of glulam timber for large structural members, development of the glulam panel deck, and treatment with modern pressure-impregnated preservatives have been major factors in advancing timber bridge technology, Also, timber is a renewable material of competitive cost with low energy of production. In the face of high steel costs and associated long delivery times, timber bridges are economical and specifically suitable for short and medium span bridges.

The evolution evident in bridge construction has not been paralleled by improvements in the associated design procedures. Though design methods for the individual stringers and decking have been modernized, these components actually act together as a unit. Present methods ignore the available interaction and a need has existed for including such effects. Current design methods, based on out-of-date information not applicable to timber systems, must be updated to include effects of existing composite action between the stringers and the deck. A full evaluation of this component interaction and incorporation of its recognition into new design procedures for glulam bridges is critical to the modernization badly needed to take full advantage of this new concept in bridge construction. Improved methods of analysis will lead to smaller required sizes and permit efficient utilization of our nation's timber resources.

2. DESCRIPTION OF THE GLULAM BRIDGE SYSTEM

2.1 General Description

Glulam bridges are best suited for rural roadways where the site requires a short-to-medium span structure. The most common type is the longitudinal stringer bridge. Normally simply-supported, stringer bridges provide economic spans of 20 to 80 feet. The modern version of this bridge is a system which contains glulam girders and deck panels as the major components. The American Institute of Timber Construction (AITC) has published plans and details for glulam bridges (1)* which are recommended for general use. Stringers employed generally range in width from 5 1/8" to 12 1/4" with varying depths. Deck panels are comprised of nominal 2-inch material vertically laminated to form a flat slab. Placed transverse to the stringers,

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* Numbers in parenthesis refer to references listed in Section 9 of the report.

the panels are generally 4-feet in width with a length equal to the full bridge width. The panel depth depends upon the conditions and 5 1/8" or 6 3/4" thicknesses are usual practice. Connection devices are critical features in the glulam bridge system. Steel dowels are employed to achieve shear and moment transfer between adjacent deck panels. Lag bolts provide interconnection of the deck panels to the stringers. The result is a two-layer structural system in which the two components interact to share the loads induced by the passage of traffic.

2.2 General Composite Behavior

Generally, layered systems perform at their maximum structural capability if the individual layers perform as if they were a single unit. The effectiveness of the mechanical connectors is measured by their ability to render the system functionally monolithic. If the mechanical connectors provide full transfer of forces and complete strain compatibility at the layer interfaces and at discontinuities in the layers, "complete composite behavior" results. Most mechanical fasteners cannot fully accomplish this behavior. The degree to which the glulam bridge system exhibits composite action and the effects of connection details on system behavior constitutes the major subject matter of this report. To facilitate reading the report, several definitions concerning composite action are provided as introductory material.

Interlayer slip, or relative motion between adjoining layers of a system, results when the connection between layers is not perfectly rigid. Such is the case for nails, bolts, and elastomeric glues. The ratio between the shear force transferred between layers and the accompanying interlayer slip is given by the slip modulus, k. The slip modulus is a function of both the connector properties and the properties of the materials (stiffness, direction of grain, thickness, etc.) joined in the vicinity of the connector. Because of the interlayer slip, the occurrence of shear lag, and gaps between bridge deck panels, the composite behavior of the layers acting together is one of incomplete composite action. The deck and stringer layers do not act together as efficiently as a rigidly connected T-beam, but are stiffer than the stringer acting alone.

3. PROJECT OBJECTIVES

In the fall of 1975, an interdisciplinary team of researchers was organized at Colorado State University under the sponsorship of the Engineering Foundation (Grant #RC-A-74-6) to analytically determine and experimentally verify the degree of composite action present in the glulam stringer bridge system. Material support for specimens was provided by AITC. The fundamental objective of the project was to develop a sound mathematical model for this system which recognizes the bridge as a multilayer, orthotropic, planar structure with only partial (incomplete) composite action due to discontinuities in the decking, and the nature of its mechanical fasteners. The basic approach was to develop a computer program which incorporates the mathematical model and to perform verification testing of reduced-scale specimens. These specimens (detailed subsequently) were essentially double T-beams comprised of glulam girders with glulam deck flanges. Test data and analytical results are presented to provide basic understanding of the behavior of the glulam bridge systems. The dimensions of the test specimens provided a range of sizes compatible with those of actual bridge configurations used in the field and permitted reliable extrapolation to larger sizes. In this way the successful agreement between theory and the test data obtained permit understanding of the overall system behavior and the parameters which influence system performance.

The specific research tasks consisted of the following:

a. Mathematical Modeling

b. Materials Testing

c. Testing of Mechanical Fasteners

d. Design and Construction of Test Framework

e. Non-Destructive and Destructive Structural Testing

f. Data Reduction

g. Extrapolation to Full Size Glulam Bridges

Details of these investigations, typical results, conclusions and recommendations are presented in this report. More extensive and elaborate descriptions of all aspects of the study will be compiled in a Masters Thesis (8) to be completed in the near future.

4. MATHEMATICAL MODEL

Closed form solutions for layered wood systems have been presented by earlier researchers (3,4,5). Unfortunately, the governing equations developed in their work are strictly correct only if the material properties of the individual layers are constant along the entire span. For wood itself, whose properties are affected by the presence of knots, orientation of the grain, moisture content, and the natural variability of the material, this is not true. Consequently, to obtain classical solutions, the design must be content with an analysis based upon average values for the necessary material properties. In the glulam bridge system, the designer must not only contend with two layers of different orthotropic properties, but also with the interlayer slip inherent with mechanical fasteners which have a major effect on the deflections and stresses of the system. In addition, the steel dowel connections commonly used to interconnect the bridge deck panels, create gaps which have a significant effect on the composite action of the system. These factors require a sophisticated method of analysis for a proper prediction of behavior. The finite difference method or finite element method (6,9) offers the capability of accounting for such effects.

A finite element approach formulated by Thompson, et al. (9), has proven successful for a number of layered systems, Kuo (7), Tremblay (10), Vanderbilt, et al. (11). Thompson's finite element is based upon the principle of minimum potential energy. Strain energy expressions from the following sources are evaluated for the solution of the layered beam problem:

1. flexure of each layer,
2. axial elongation of each layer,
3. slip deformation of the connectors between each layer, and
4. external loads on the system.

By including all the potential energy resulting from the forces above, the total potential energy of an m-layered beam is

$$\pi_p = \sum_{i=1}^{n_L} \int_0^{\ell} \left[\frac{1}{2} E_i I_i \left(\frac{d^2y}{dx^2}\right)^2\right] dx + \sum_{i=1}^{n_L} \int_0^{\ell} \left[\frac{1}{2} E_i A_i \left(\frac{du_i}{dx}\right)^2\right] dx$$

$$+ \sum_{i=1}^{n_L-1} \int_0^{\ell} \frac{1}{2} \left(\frac{k_i n_i}{s_i}\right) \left[(u_{i+1} - u_i) - \frac{1}{2}(h_{i+1} + h_i) \frac{dy}{dx}\right]^2 dx$$

$$- \int_0^{\ell} w(y) dx \qquad (4.1)$$

where i = "for layer i",

n_L = the number of layers,

E_i = modulus of elasticity of layer i,

I_i = moment of inertia of layer i,

A_i = cross-sectional area of layer i,

k_i = slip modulus of connector between layers i and $i+1$,

n_i = number of rows of connectors between layers i and $i+1$,

s_i = spacing of connectors between layers i and $i+1$,

h_i = depth of layer i,

w = beam loading,

x = length along the beam,

y = vertical displacement of the beam,

ℓ = beam length,

and u_i = axial displacement of layer i.

The first and second terms in Eq. 4.1 are the flexural and axial strain energies, respectively, and the last term is the work due to w. Energy losses due to interlayer slip are accounted for in the third term which was developed by Thompson, et al. (9). In formulating the first and fourth terms, it is necessary to assume that the individual layers have identical curvature.

The principle of minimum potential energy requires that the first variation of π_p be equal to zero for the equilibrium position of the structure. Consequently

$$\delta\pi_p = 0 \tag{4.2}$$

or

$$
\sum_{i=1}^{n_L}\left[\int_0^{\ell} E_i I_i\left(\frac{d^2y}{dx^2}\right)\delta\left(\frac{d^2y}{dx^2}\right)dx\right.
$$

$$
\left.+\int_0^{\ell} E_i A_i\left(\frac{du_i}{dx}\right)\delta\left(\frac{du_i}{dx}\right)dx\right]+\sum_{i=1}^{n_L-1}\left\{\int_0^{\ell}\left(\frac{k_i n_i}{s_i}\right)\left[(u_{i+1}-u_i)\right.\right.
$$

$$
\left.-\frac{1}{2}(h_{i+1}+h_i)\frac{dy}{dx}\right]\delta(u_{i+1}-u_i)dx-\int_0^{\ell}\left(\frac{k_i n_i}{s_i}\right)\left[(u_{i+1}-u_i)\right.
$$

$$
\left.\left.-\frac{1}{2}(h_{i+1}+h_i)\frac{dx}{dy}\right]\frac{1}{2}(h_{i+1}+h_i)\,\delta\left(\frac{dy}{dx}\right)dx\right\}-\int_0^{\ell} w\delta y\,dx=0 \qquad (4.3)
$$

The finite element approach consists of dividing the layered beam into a series of longitudinal elements interconnected at node points. The Rayleigh-Ritz procedure; i.e., using approximation functions for the various displacements needed to evaluate Eq. 4.3, is applied to each element. As described by Thompson, et al. (9), suitable functions in matrix form are

$$
y_u = [N_y]\,\{Y\}_j \qquad (4.4)
$$

$$
u_{ij} = [N_u]\,\{U_i\}_j \qquad (4.5)
$$

in which $[N_y]$ = shape functions for a cubic approximation to y for element j,

$[N_u]$ = shape functions for a linear approximation to u for element j.

$\{Y\}_j$ = unknown vertical deflections and slopes at the ends of element j,

and $\{U_i\}_j$ = unknown axial deformations at the ends of layer i of element j.

Substitution of Eqs. 4.4 and 4.5 into Eq. 4.3 permits expressing the variation of potential energy attributed to element j in the form

$$\delta\pi_{pj} = \{\delta\Delta\}_j^T [k_e]_j \{\Delta\}_j - \{\delta\Delta\}_j^T \{f\}_j \tag{4.6}$$

in which $\{\Delta\}_j$ = column matrix containing the unknown displacement quantities,

$\{k_e\}_j$ = stiffness matrix for element j,

and $\{f\}_j$ = an array for nodal forces for element j as produced by the applied loads.

The system variation of potential energy is obtained by summing, figuratively, the contributions of all elements to obtain

$$\delta\pi_p = \{\delta\Delta\}^T [K] \{\Delta\} - \{\delta\Delta\}^T \{F\} \tag{4.7}$$

The condition that Eq. 4.7 equates to zero for all disturbances $\delta\Delta$ requires that

$$[K] \{\Delta\} - \{F\} = 0 \tag{4.8}$$

where [K] is the structure stiffness matrix,

[F] is the entire set of nodal forces,

and [Δ] is the entire set of unknown displacement quantities, which are the equilibrium conditions one expects to obtain by minimizing the potential energy. Application of boundary conditions and solving for the displacement quantities follows conventional procedures. The summation of element contributions referred to in obtaining Eq. 4.7 is accomplished by building [K] by the usual "direct element method" of feeding the element stiffness matrices into their proper locations.

Two techniques for modeling gaps in the layers of the beam have been employed by Thompson, et al. (9). Either a "special" element or a "soft" element can be employed. The special element consists of releasing the continuity of axial force at the gapped location. This is accomplished by making the axial force of the two elements adjacent to the gap independent of each other and is similar to releasing the moment at an internal hinge of a framed structure. A soft element is an element of finite, but small, length with a low modulus of elasticity, placed at the gap location. Even at low modulus values, instability is never approached provided at least one layer is continuous at the gap.

A computer program was written to employ the finite element model in the analytical studies presented in this report. Theoretical solutions were obtained by this method for the actual test specimens and by extrapolation to full-size bridge configurations. As a prelude to subsequent discussion of the project results it is useful to describe the concept of a "composite-action curve", the usual output of the computer program.

From both the conceptual and performance point of view, it is vital to investigate interlayer slip and gaps as they are key parameters which influence the behavior of layered systems. The composite action curve is the mode for accomplishing this. A typical example of such a curve is presented in Fig. 1. This figure illustrates the influence of the degree of composite action developed by the flange-to-beam connection on the deflection behavior of a T-beam. It is evident that as the degree of composite action, as measured by the slip modulus of the connectors, k, increases, the deflection of the T-beam decreases. Using Fig. 1 as an example of the expected behavior of a typical bridge T-beam, the predicted deflection, for a slip modulus of 42,000 pounds per inch, is shown to be about 76 percent of the 1.14 inch deflection exhibited if the composite action gained by the connection to the deck is ignored.

In addition it must be noted that the general shape of the curve and its plotted position are a function of deck's gap condition. As the gap condition changes from completely discontinuous deck (open gaps), to partially continuous deck (e.g. dowel connectors), to completely continuous deck (no gaps) the system stiffness for the full range of slip moduli increases and consequently lower deflections are realized. A major thrust of the work reported herein is to establish such curves as verification of the test program and to extrapolate the observations to the understanding of full-size bridge structures.

5. STRUCTURAL TESTING

5.1 Description of Test Specimens

A wide range of test specimens were used, to provide verification of the model on a broad basis. Six twin T-beams, with the configuration shown in Fig. 2, were built and tested. Three specimens were comprised entirely (deck and stringers) of Southern pine and three were entirely Douglas-fir. The stringer types and sizes are listed in Table 1. Deck panels, as shown in Fig. 3, were fabricated in the generally standard 4 ft. width with a reduced thickness of 3 1/8 in. Holes for 3/4" ϕ lag bolts (drilled during erection) were placed at the recommended locations 8 inches in from the longitudinal edge of the deck panels and 1'8" from the transverse edge to align with the stringers.

5.2 Test Set-up and Procedure

Facilities used for the structural testing of the glulam bridge specimens are located in the structural engineering laboratory at the Engineering Research Center, Colorado State University. The test framework, specially constructed for this project, is schematically illustrated in Fig. 4. The system consists of a pair of overhead steel frames which, at the inception of loading, lift into bearing against the lip of a massive concrete pad which is tied to the existing floor slab thus forming a closed frame. Roller supports make the steel frames movable permitting load positioning or complete removal of the steel components during the erection sequence. The movable frames are equipped with a single 100 kip capacity hydraulic actuator, associated load cells and control equipment. Data acquisition was provided by an automatic data logger system, consisting of 100 channels of recording and signal conditioning, along with appropriate transducers to measure strains, deflections, and interlayer slip of the test specimens.

Twin T-beam configurations were used for the test specimens primarily to provide necessary lateral stability. A clear span of 39 ft. 6 in. was employed for all specimens. Two concentrated loads were applied to spreader beams placed 4 feet apart (2 feet each side of midspan). The spreader beams were placed in a manner which divided the concentrated load equally to each of the twin T-beams. The spreader beam reactions were transmitted to the deck through 12" x 14" bearing plates located directly above the stringers.

This loading assured direct transmission of the loads to the stringers thus eliminating load distribution considerations which were not a part of this study.

The procedure for each twin T-beam tested was:

1) Install and grout appropriate end support framework.
2) Install the girders.
3) Install instrumentation for strain and deflection.
4) Determine MOE's for each beam by loading within the working load range.
5) Attach the deck panels.
6) Add slip instrumentation.
7) Install spreader beams.
8) Conduct tests at working load range to assess composite behavior of the specimen.
9) Remove instrumentation.
10) Test to failure and photograph.
11) Disassemble, label and store for subsequent slip tests.

Details of the erection procedure for the complete specimens were essentially the same in each case:

In order to construct each bridge within the range of the test frame loading actuators, it was necessary to have an adjustable-type end support system to accommodate the various beam depths used. This was accomplished by using 55 gallon drums filled with concrete, with a variable number of 1½" thick circular mortar blocks grouted to the top of each concrete drum. With the drums permanently in place, each bridge system was accommodated by installing the appropriate number of mortar blocks, prior to installation of the girders. A crane was then employed for actual placement of the girders, which after alignment were temporarily braced for construction purposes. Deck panels were manually lifted on to the girders and slid into their approximate final position. This provided an excellent working surface and minimized the time for costly labor and crane services. The force required to join deck panels was provided by a horizontal hydraulic jacking system, see Fig. 5.

Assembly proceeded systematically from one end of the bridge to completion at the other end. The first deck panel had to be carefully aligned with the girders, then lag bolted in place. Having accomplished this, each adjacent deck panel was then jacked into place and lag bolted. Panels were jacked together as tightly as possible without sacrificing alignment. A positive jacking platform was provided by the unassembled deck panels butted together along the remaining length of the span. These were held fixed by a set of stop blocks spiked at the far end to the girders. Having assembled all possible panels in this way, the stop blocks were removed and the last panel fitted with the use of a sledge hammer. This systematic method of assembly was fast and efficient, keeping on-site labor to a minimum. An average of twenty four man hours (two man crew) was required for assembly of each complete specimen.

Deflection and slip measurements at various working levels were obtained from recordings generated by the data logger equipment. Displacement transducers were placed below each stringer at several locations along the span. Slip measurements were measured at six locations along the deck-stringer interface by mounting displacement transducers and blocking to permit monitoring of the relative motion of the two components. Strain measurements were taken at centerline of each stringer by attaching strain transducers at selected points throughout the depth of each girder.

During the test to failure, all instrumentation was removed to avoid possible damage. However, midspan displacements were monitored by mounting scales at midspan and tracing the motion of the girders.

6. TESTING OF MATERIALS AND MECHANICAL FASTENERS

The properties of the materials which comprise the test specimens and also the full-scale bridge systems are an important influence in their behavior. Thus for verification of the model and for its future use in design, knowledge of these material properties is important.

For the first phase of the study the mathematical model was employed to predict the deflection of the T-beam specimens when loaded within the elastic range. Since the structural tests were subsequently carried out to destruction, some elastic properties had to be determined by non-destructive test procedures prior to the tests to failure. The modulus of elasticity (MOE) for each test girder was obtained by a simple beam flexural test of the individual girders. Two concentrated loads, four feet apart, were symmetrically placed about the midspan. Midspan deflections needed for computation of the MOE were recorded by displacement transducers.

A limited number of deck panels were tested in a similar configuration for determination of their MOE values. However, preliminary analytical studies indicated that for the reduced scale specimens (specifically, the thinner deck panels) the deck MOE value was of only minor influence. Thus, the average MOE values as reported by Bodig and Goodman (2), for each of the two wood species employed, was adopted for use in the computer programs. Moisture content readings, taken as close to the time of testing as possible, exhibited a range of values between 7.0% and 17.5% for Southern pine and between 7.4% and 12.3% for Douglas-fir. The average values were 9.6% and 10.6% for Southern pine and Douglas-fir, respectively.

The magnitude of the interlayer slip is a function of the interlayer connection. The stiffness of this connection, i.e. the slip modulus, must be evaluated to permit proper analysis of the bridge specimens. To accomplish this determination, a special laboratory device, capable of accurate measurement of the behavior of the lag bolt connection between the deck panels and bridge beams, was constructed. By use of this device a specimen comprised of a small piece of deck panel and bridge girder, fastened together by a single lag bolt may be tested in a single shear configuration. The result is a "slip curve" of the nature shown in Fig. 6. Theoretically the slip modulus can be defined as the tangent to the curve at the applicable load level or as an appropriate secant modulus. Since measured and computed slip values ranged up to 0.005 in., the secant at the 0.010 in. slip level was adopted for this study. Values for this parameter are presented in Table 2. Two slip specimens were made for each girder for a total of 24 slip tests. The average values of slip modulus obtained were 47,000 k/in and 46,000 k/in for Southern pine and Douglas-fir, respectively. The overall average for both species combined was 46,800 k/in.

7. RESULTS OF VERIFICATION TESTS

A goal of the research described in this report was to develop a mathematical model for layered beam systems applicable to the glulam bridge problem and perform verification tests on carefully selected reduced-scale specimens. Accomplishment of this goal permits a rational analysis of the behavior of full-size bridges. Composite action curves developed subsequently are the tools for this rational analysis.

7.1 Composite Action Curves

As defined earlier, the composite action curve permits understanding of the effects of key parameters on the stiffness of a layered beam system.

Composite action curves generated for each test configuration are presented in Figs. 7 through 12. Curves illustrated in Fig. 7 are for the Southern pine T-beam specimen SP-25.5 and will be used for discussion purposes. The curves are derived for the specific loading condition used in the structural test, i.e. two concentrated loads, one two feet to each side of midspan. Midspan deflections are plotted versus slip modulus values for three different conditions. The abscissa is put in non-dimensional form by normalizing the displacement values relative to the theoretical non-composite deflection (Δ_N). Each of the presented curves is representative of a different interpanel gap condition and each demonstrates the effect of slip modulus on the composite behavior. The lowermost curve represents a completely continuous deck system, i.e. no gaps in the decking. The uppermost curve represents a discontinuous deck system in which the individual deck panels have no interface transfer of shear or moment, i.e. complete open space between panels. The intermediate curve constitutes a gap condition which is between the two extremes.

Inspecting any of the three curves, it is evident and expected, that as the slip modulus increases the stiffness of the system increases. At low k values, essentially no composite action is realized regardless of the gap condition. At an infinite k value all three converge to the rigid system (fully composite) deflection value. The vertical distance between these two extreme levels constitutes the maximum possible percentage reduction in deflection. This magnitude of reduction can be achieved only under ideal conditions, namely no gaps and a monolithic cross-section. For the particular structure represented in Fig. 7, a 22% reduction is possible at the ideal limit.

Due to the presence of mechanical fasteners, actual test specimens do not achieve the total reduction in deflection which is theoretically possible, i.e. incomplete interlayer connection reduces the efficiency of the system. The composite action curves graphically display this behavior. The vertical distance above the NO GAPS composite action curve constitutes the percentage reduction in deflection available for given k values. This represents the loss of stiffness attributable to the use of a specified number and size of lag bolts for the deck-to-stringer connection. In addition, the presence of gaps in the deck further affects the composite action. As E/L, a measure of gap stiffness, decreases, the composite action curve assumes a higher position. Thus, in effect, for a given k value, the observed composite action decreases as E/L is lowered (the nature of the gaps is worsened) reaching a limit at the GAPS composite action curve. The vertical distance above the GAPS composite action curve indicates that for large k values some composite behavior is guaranteed.

For purposes of this study the composite action curve and test data are employed in the following way. The developed mathematical model is used to generate the extreme case composite action curves (GAPS and NO GAPS) for each test specimen. The slip modulus value is determined experimentally using the single-shear test apparatus mentioned earlier. Midspan deflection is measured during the working load test. The position of the plotted data point between the two extreme curves permits assessment of the composite behavior of the test specimens. For specimen SP-25.5 illustrated in Fig. 7, the recorded displacement was 0.86 inches and the theoretical value of Δ_N was .93 in giving a Δ/Δ_N = .925. Table 2 indicates the average slip modulus for material specimens taken from this specimen was 53,000 kips/in. The plot of these coordinates is shown as a "+" in Fig. 7. The graphical results can be used to make qualitative assessment of the performance of the test specimens and provide a basis for extrapolation to full-size bridges as discussed subsequently.

7.2 Numerical Results

A procedure for the quantitative study of the test results can be developed. Fig. 13 illustrates and defines the quantities utilized in the procedure. Load-deflection curves are shown, in general, for the two extremes of composite behavior and for the incomplete composite behavior which is typical of actual layered systems. The maximum percentage composite action available (C.A.A.) is that realized by the completely composite sytem and is given by

$$\text{C.A.A.} = \frac{\Delta_N - \Delta_C}{\Delta_N} \tag{7.1}$$

in which Δ_N = the theoretical deflection of the system if the behavior is not composite,

and Δ_C = the theoretical deflection of the system if the behavior is completely composite

The efficiency (EFF) exhibited by the actual layered systems (percentage of the C.A.A. which is achieved) is given by

$$\text{EFF} = \frac{\Delta_N - \Delta_I}{\Delta_N - \Delta_C} \tag{7.2}$$

where Δ_I = the measured deflection.

The percentage of composite action observed (C.A.O.) in the real system is obtained by

$$\text{C.A.O.} = \text{EFF} \times \text{C.A.A.} \tag{7.3}$$

For specimen SP-25.5 the values computed for Δ_N and Δ_C were 0.93 and 0.735 in., respectively. In the structural test Δ_I was recorded as 0.86 in. These values imply 20.5% C.A.A., 36.8% EFF and 7.5% C.A.O. for the specimen. While the composite action observed (7.5%) is low, it is a value which applies to the test specimen only.

Table 3 is a complete compilation of the experimental and theoretical results for the six test specimens. The MOE values listed are the average value for the two stringers. Load values, P and P_{FAIL}, listed are the loads applied to the girder by the spreader beam reaction (in the working load and failure load tests, respectively). The composite action available ranged between 18% and 34% and between 17% and 27% for the Southern pine and Douglas-fir species, respectively. The last two columns compare the modulus of rupture, MOR, based upon the section modulus of the stringer alone with the theoretical stress at the failure load. The inherent reduction in stress due to composite action indicated by these two columns has important implications on the ultimate load capacity of the full-size bridge system. In two of the specimens, SP-21 and SP-30, the working load tests were repeated after shimming the gaps between deck panels with wood material where possible. Under these conditions the efficiency of the system was greatly improved as evident by a near doubling of the EFF values. The EFF values increased from 23.5% to 44.2% and from 19.3% to 37.6% for the SP-21 and SP-30 specimens, respectively. These changes reflect the great significance gap condition has on the performance of the system. It must be noted that the shims were left in place during the test to destruction. Consequently, their influence also may have been reflected in the ultimate strengths.

7.3 Observations from Test Program Results

The results of the various test programs including measurement of material properties and reduced-scale T-beam tests have been summarized in the preceding section. These results serve to provide a basis for the understanding of the key variables which affect the performance of the glulam bridge system. The verification of the developed mathematical model has been accomplished within the limitations of the measurement of input variables which have been found to have a major influence on the performance of the system. Application of the developed mathematical model can then be made to allow the calculation of the performance of full-size bridges.

Some observations regarding the influence of certain key variables are in order to more fully explain the results obtained in the reduced-scale T-beam tests. In addition to the usual geometric and material property variables such as span, beam spacing, size of members, stiffness of beams, etc., three additional key variables were found to have a large effect on the system performance. These variables are 1) the degree of interlayer connection as represented by the size and number of lag bolts which is included in the mathematical model as "slip modulus", 2) the inherent stiffness of the glulam deck material in the direction of the girders defined as "deck MOE", and 3) the type and nature of the gaps between individual deck panels for which a parameter measuring the stiffness of the gap was developed and defined as "E/L". Each of these key variables will be discussed.

The "slip modulus" is a function of the size and number of lag bolts provided for each deck panel. Measurements of this variable were made as described. Opportunities for improving the degree of connection of the deck and girders are possible by increasing the number of lag bolts or by changing the size of the bolts. Full-size bridge systems will demonstrate a generally higher slip modulus than the reduced-scale system due to larger bolts used and the influence of thicker deck panels.

The "deck MOE" of the panels in the direction of the girders is relatively low since the perpendicular-to-the-grain stiffness is the value effective. Further discussion of possible articulations of bridge deck systems and the implication of this parameter for full-size bridges will be given in a following section of the report.

The type and nature of gaps between deck panels which give rise to loss of continuity of the deck flange of the composite system was found to have a critical effect in the performance of the reduced-scale system. Quantification of this effect through measurement of a stiffness parameter, "E/L", is currently being accomplished by additional testing as described in a later section of the report. The thinner deck (3 1/8") used in the reduced-scale system as opposed to the usual deck thickness of the full-sized bridges (5 1/8" to 6 3/4") is felt to be the primary cause of the large gap effect observed in the reduced-scale test results. The thickness of the deck gave rise to construction difficulties in panel alignment due to warping (a problem not encountered in normal size deck panels). Thus, the gaps were not fully butted in most cases and the continuity was interrupted to a larger degree than expected in thicker deck. Full-size deck panels are now being tested to assess the influence of deck thickness on the behavior of the gaps between panels. These results will provide the needed input data to allow computation of behavior of the full-size glulam system.

Thus, overall results of the test program were highly successful in defining the necessary parameters required to properly assess the performance of the glulam bridge system. A mathematical model has been developed which will permit the rational analysis of such systems to provide the engineering community with a sound basis for improving their design.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Implications for Full Size-Systems

The test program and mathematical studies conducted in this project have resulted in a physical and theoretical understanding of the glulam bridge system. A mathematical model has been developed to produce composite action curves, given in Figs. 7-12, for the six T-beam specimens tested in the laboratory. While these particular curves give great insight into the nature of the composite behavior layered T-beams, they, by themselves, do not offer direct quantitative indications of the performance to be expected in full-size bridges. Specifically, the curves have been generated for the test specimen cross-sections which have reduced scale dimensions and are limited to the span and load arrangement used in the actual physical tests. However, by extrapolating the dimensions to full-size cross-sections and regenerating the composite action curves, valuable comparisons can be made.

Fig. 14 illustrates composite action curves for a cross-section whose dimensions are realistic for a 39'-6" span. The stringer size and span are identical with that of Fig. 10. However, the deck thickness and effective width have been increased to dimensions which would normally be used for this size stringer. The dashed curves in Fig. 14 are the extreme case composite action curves for this larger cross-section. When compared with Fig. 10, the change in performance observed is dramatic. The most significant observation to be made is that at the ideal limit ($k = \infty$) a reduction in deflection of the order of 48% is possible. This is twice the 24% possible reduction evident in the reduced scale counterpart presented in Fig. 10. Clearly, this demonstrates that the quantitative results for the test specimens are highly conservative estimates of the composite action available in real systems.

One major deficiency in the glulam bridge system is the orientation of the glulam deck panels. Normally, the need to safely span from stringer to stringer requires the deck panels to be aligned such that the longitudinal MOE of the deck material is effective in that direction. This necessitates having the significantly lower transverse MOE of the deck effective in the direction of the bridge span. Primarily, the effectiveness of the layered cross-section is greatly reduced because the transformed area of the flange is quite small. This is a major reason for the low degree of composite action observed (C.A.O. values) in the test specimens. Fig. 14 emphatically demonstrates this point. The dashed curves in Fig. 14 are based upon a cross-section in which the deck MOE is 140,000 psi (the transverse MOE value for the Douglas-fir test panels). The solid curves are generated for the same cross-section except the deck MOE has been changed to 1,900,000 psi (the longitudinal MOE for the test panels). For the solid curves the reduction in deflection at $k = \infty$ is in the order of 75%. The importance of this observation is that innovations in construction which would better orient the deck panels and take advantage of the high longitudinal MOE value would result in greatly improved composite behavior.

8.2 Future Needs

Knowledge gained in completing the project reported herein indicates that considerable composite action is possible in glulam bridge systems. Analytical results demonstrate that although test specimens exhibited a relatively low degree of composite action, dramatic improvement in performance can be achieved by correcting the physical deficiencies which cause the reduced efficiency. Primarily, changes and improvements in the construction methods are needed to minimize loss of stiffness caused by mechanical connectors, increase the continuity of the deck, and better orient the panels to use material properties to their best advantage. In this regard, the writers have already undertaken, with the sponsorship of AITC, a study of the performance of the dowel connection used for the deck panel. The aim of this new project is to quantify the stiffness of the dowel connection and the effect of dowel hole size on the behavior of the deck. Experimentation and analysis will provide a data base for an improved simulation of gap condition at the deck panel interface (a key variable in the glulam bridge mathematical model).

Consistent with needed improvements in construction, a need exists to advance the analytical methods developed in this work to make them directly applicable to actual-size glulam bridge systems. Results and observations reported herein give great insight into the performance of glulam bridges and the developed mathematical model makes needed continuation studies feasible. These future studies should be directed at critical aspects of bridge behavior which cannot be addressed with the present state of knowledge. One critical need is to perform load distribution studies to determine realistic loadings for use in generating composite action curves for full-size bridges. Effects of repeated and long term loading are also unknown and must be considered. These effects on connector performance and the overall structural behavior should be investigated. Finally, on-site testing of full-size glulam bridges subjected to moving loads is highly desirable. Such testing would provide verification of theoretical load distribution studies, provide necessary understanding of fatigue effects and eliminate size effects inherent in reduced-scale specimens.

9. CLOSURE

Successful completion of the described work lends insight into the performance of glulam bridge systems and provides designers with a rational means of analyzing such structures. This investigation has long-range implication to our national need for bridge replacement programs on rural transportation avenues and schoolbus routes. Improved analytical methods, which account for composite action, can be developed and employed to generate safe, efficient and reliable designs for the aesthetically pleasing glulam bridge structure.

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APPENDIX A

TABLES AND FIGURES

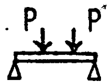
TABLE 1 STRINGER SIZES AND SPECIES

SPECIMEN NO.	SPECIES	WIDTH (IN.)	DEPTH (IN.)
SP-21	Southern pine	3	21.0
SP-25.5	Southern pine	5	25.5
SP-30	Southern pine	5	30.0
DF-25.5	Douglas-fir	3 1/8	25.5
DF-20.75	Douglas-fir	5 1/8	21.0
DF-30	Douglas-fir	5 1/8	30.0

TABLE 2 MEASURED SLIP MODULUS VALUES (K/IN)

SPECIMEN	EAST		WEST		AVG
	K_1	K_2	K_1	K_2	K
SP-21	55,000	50,000	38,000	35,000	45,000
SP-25.5	60,000	60,000	52,000	40,000	53,000
SP-30	45,000	60,000	45,000	28,000	45,000
DF-25.5	40,000	40,000	45,000	75,000	50,000
DF-21	42,000	53,000	35,000	33,000	41,000
DF-30	35,000	40,000	48,000	65,000	47,000

TABLE 3 SUMMARY - T-BEAM TEST RESULTS

SPECIMEN	$\frac{MOE}{10^3}$ (KSI)	 P (K)	WORKING LOAD RANGE Δ_N (IN)	Δ_I (IN)	Δ_C (IN)	C.A.A. (%)	EFF (%)	C.A.O. (%)	FAILURE P_{FAIL} (K)	MOR (KSI)	THEORY FAILURE STRESS (KSI)
SP-21	1.83	1	1.03	.947 .874 X	.677	34.3	23.5 44.2	8.1 15.2	5.65	5460	5000
SP-25.5	1.70	2.5	.93	.86	.735	21.0	35.9	7.5	16.0	6290	6000
SP-30	1.88	3	.62	.599 .579 X	.511	17.6	19.3 37.6	3.4 6.6	25.0	7100	6870
DF-25.5	2.13	1.75	.83	.80 XX	.608	26.7	13.5	3.6	10.3	6450	6180
DF-20.75	1.91	2	1.20	1.12	.906	24.5	27.2	6.7	9.50	5500	5225
DF-30	1.95	3	.58	.535	.48	17.2	45.0	7.7	24.0	6670	6400

X WITH SHIMS XX NO DATA EAST BEAM

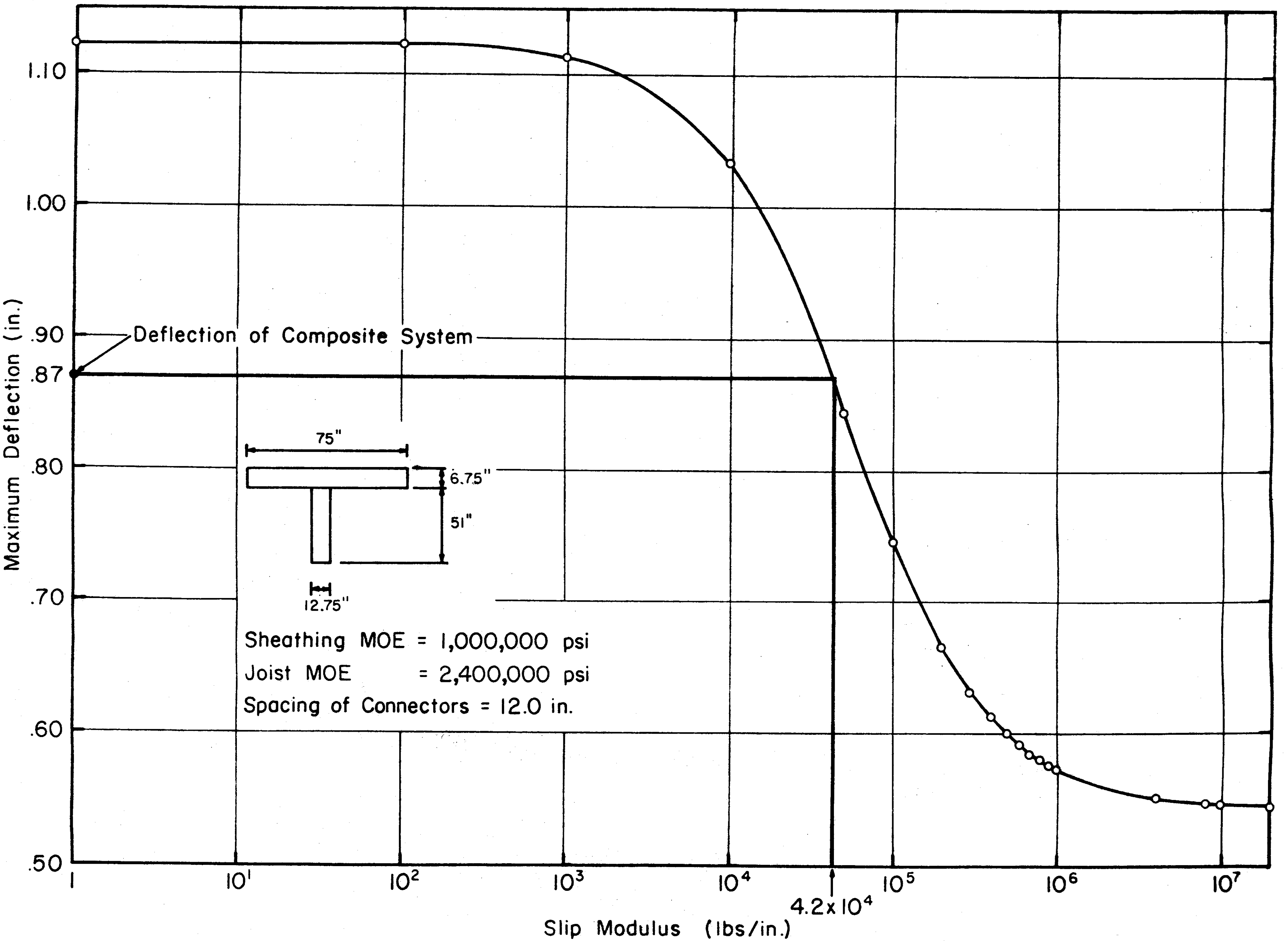
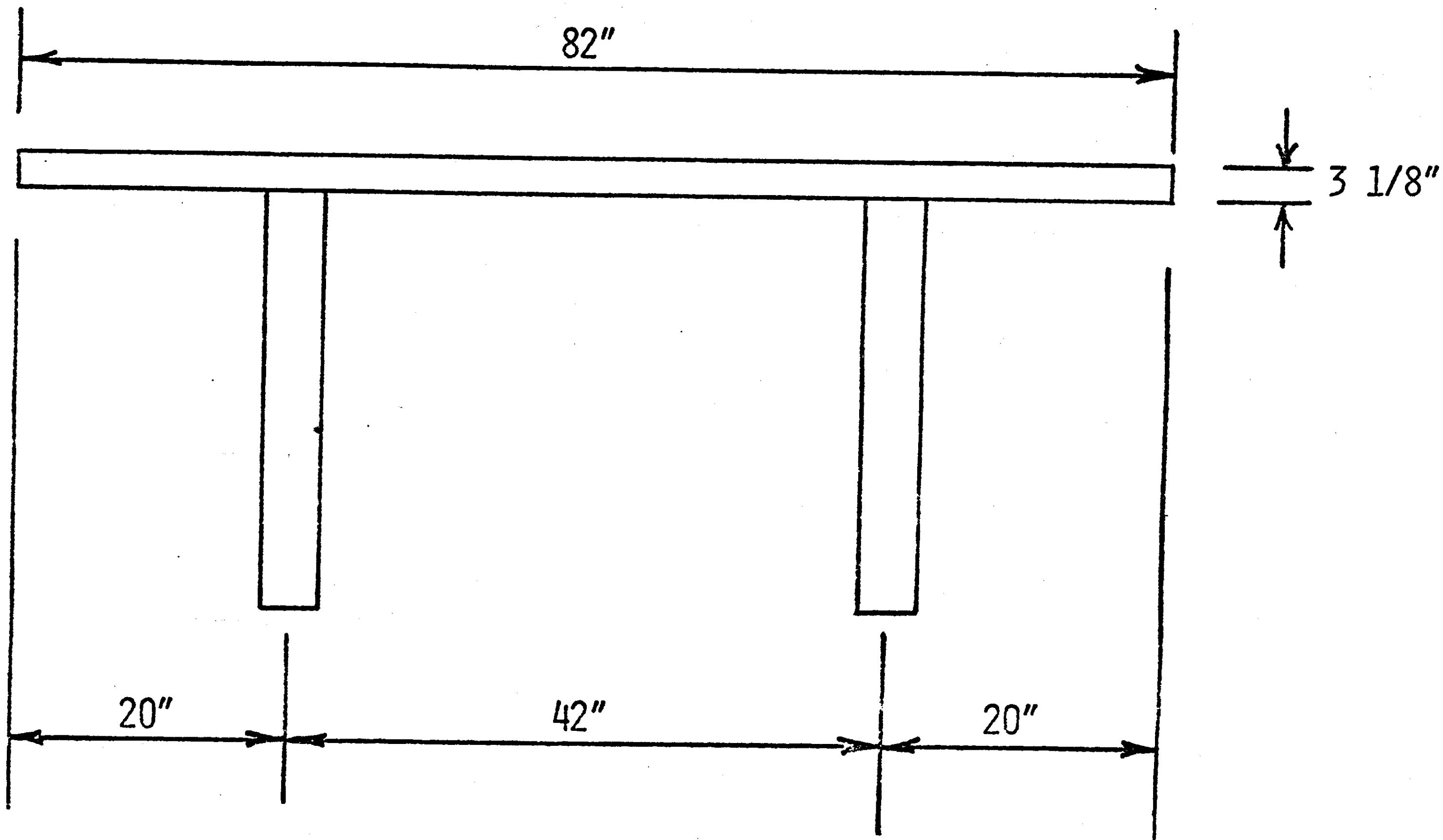


Figure 1. Composite Behavior of Typical Bridge T-Beam



TYPICAL TEST SPECIMEN (SPAN 40' - 0")

Figure 2. Twin T-Beam Cross-Section

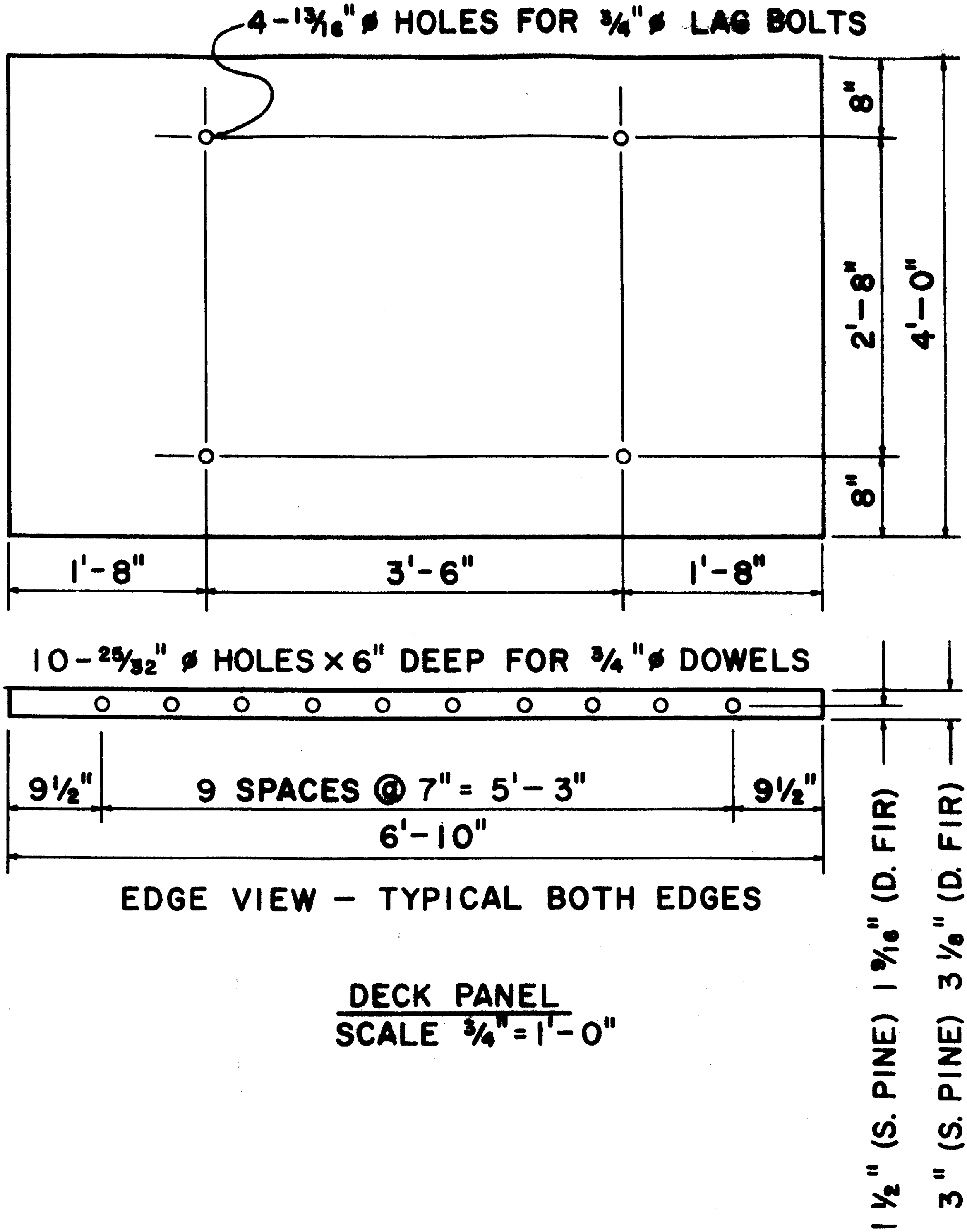


Figure 3. Deck Panel Dimensions

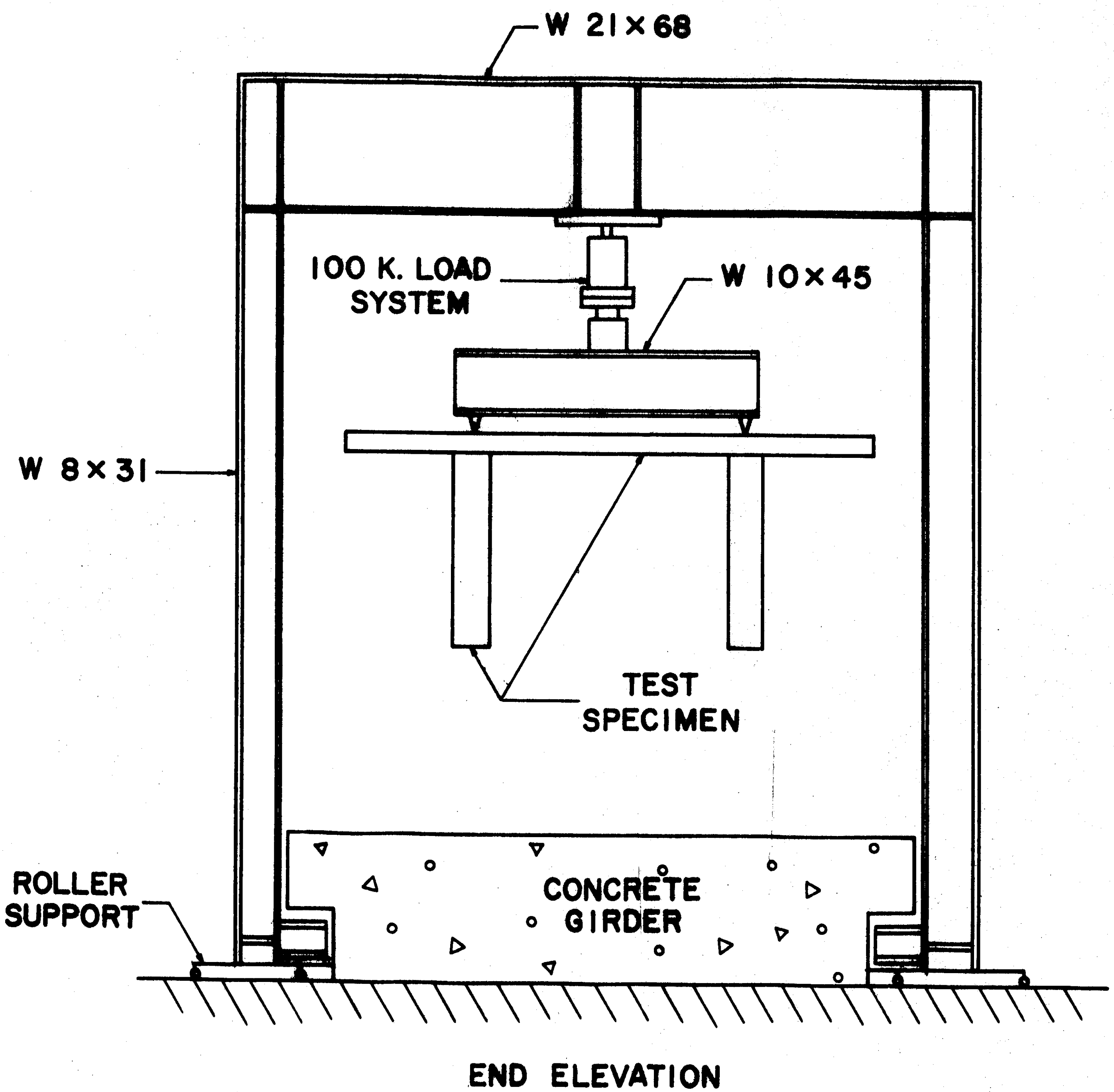


Figure 4. End View of Test Frame Arrangement

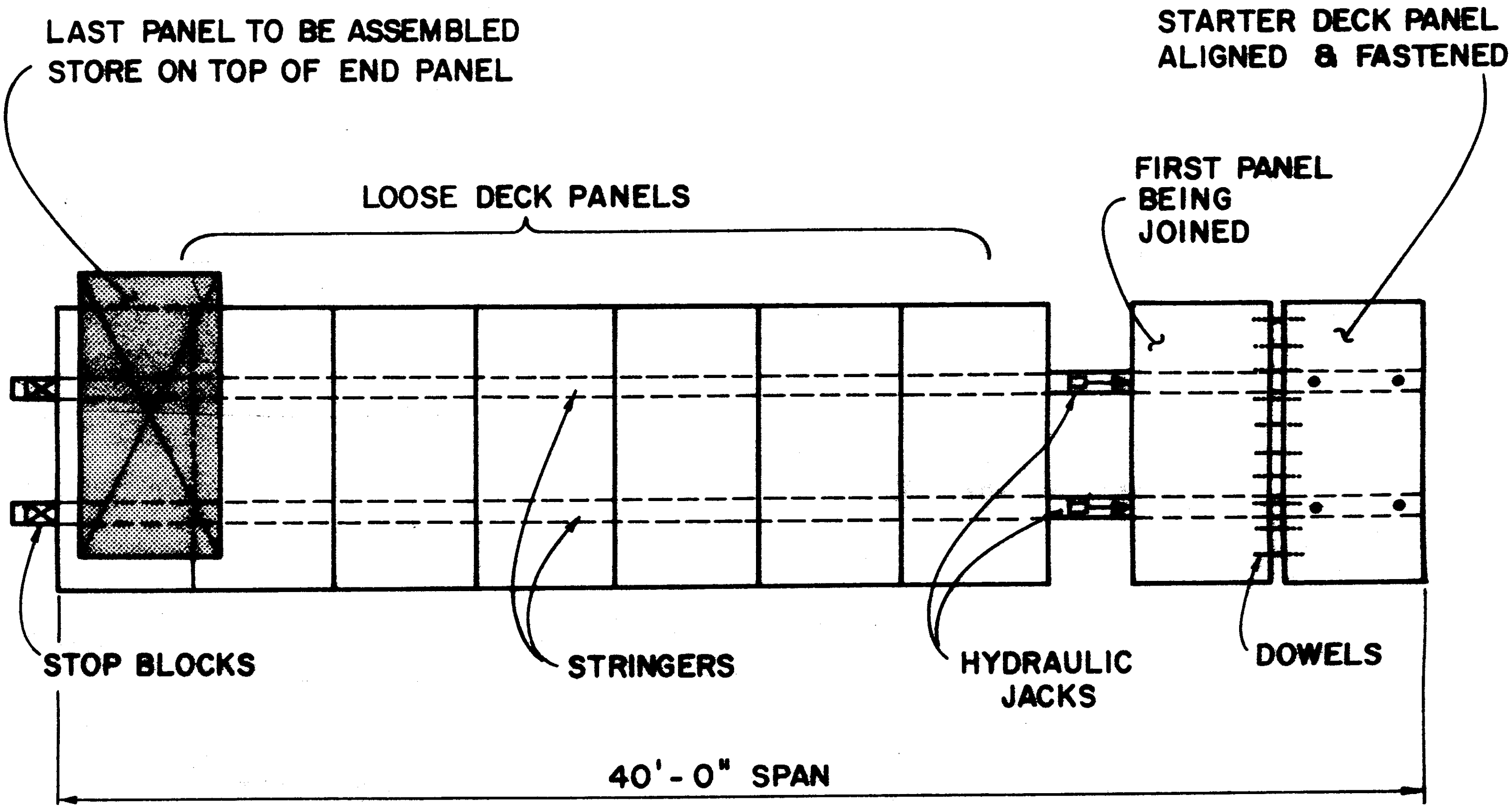


Figure 5. Erection Procedure for Typical
T-Beam Specimen

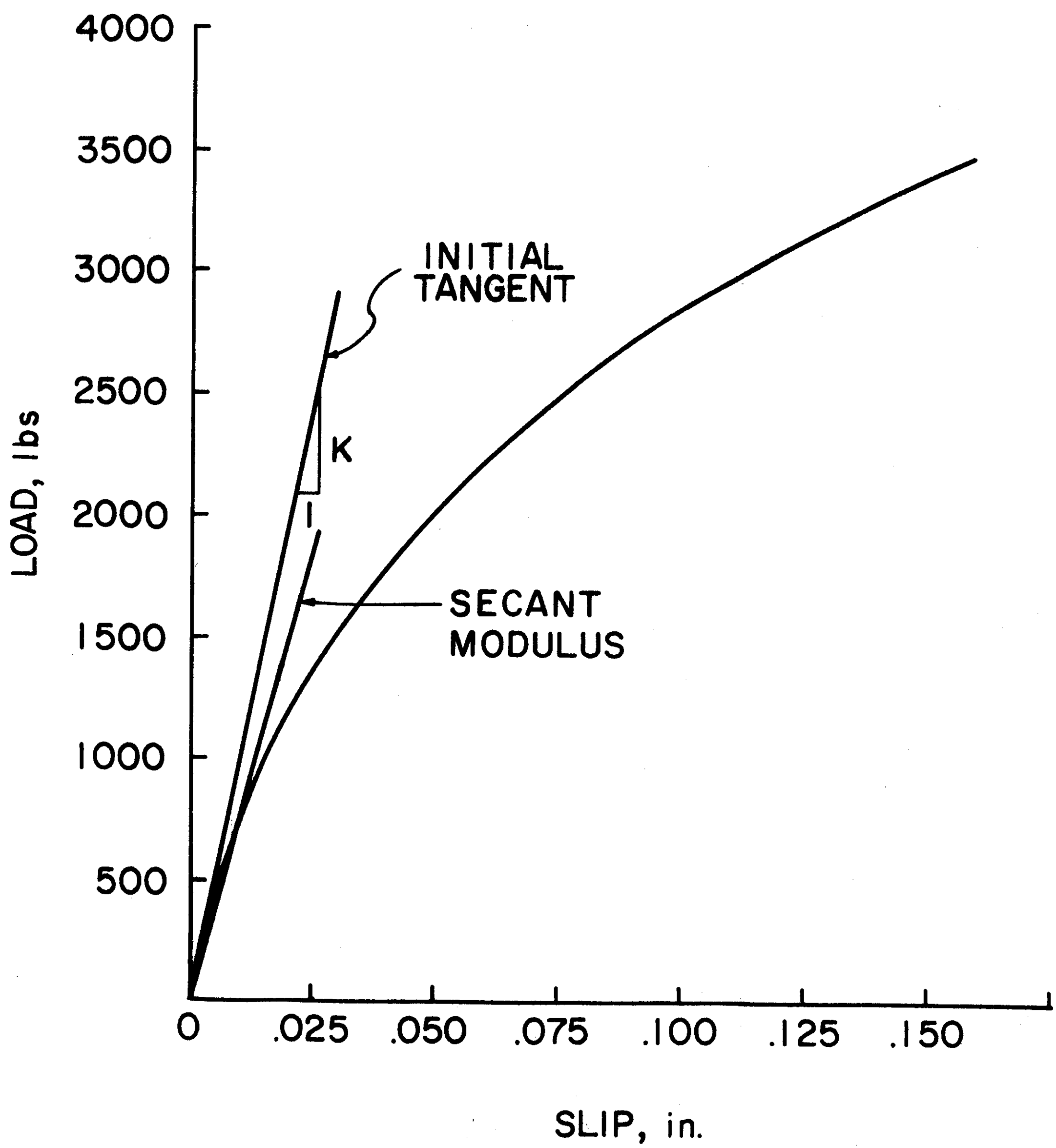


Figure 6. Typical Slip Curve for Lag Bolts

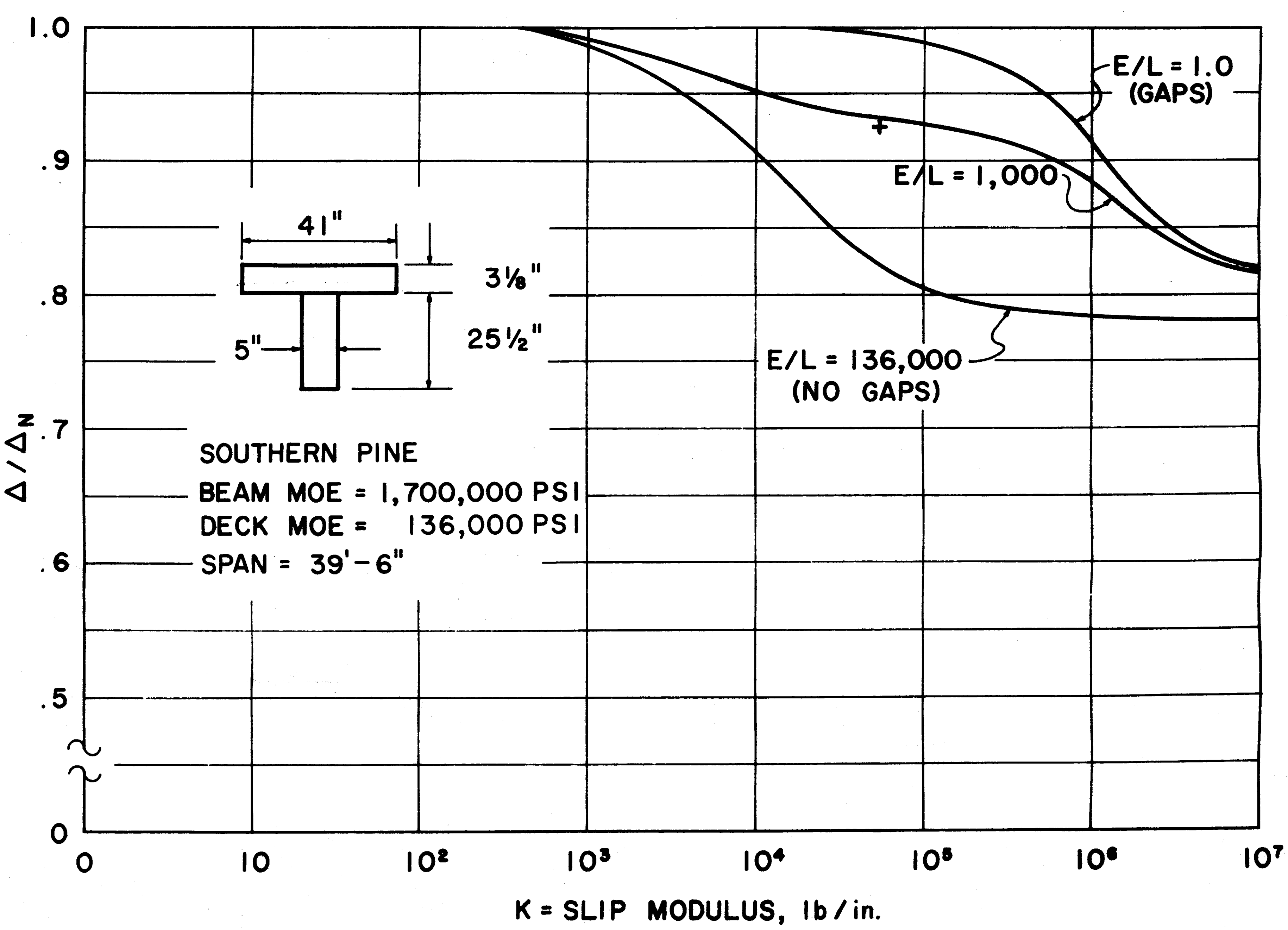


Figure 7. Composite Action Curve - Specimen SP=25.5

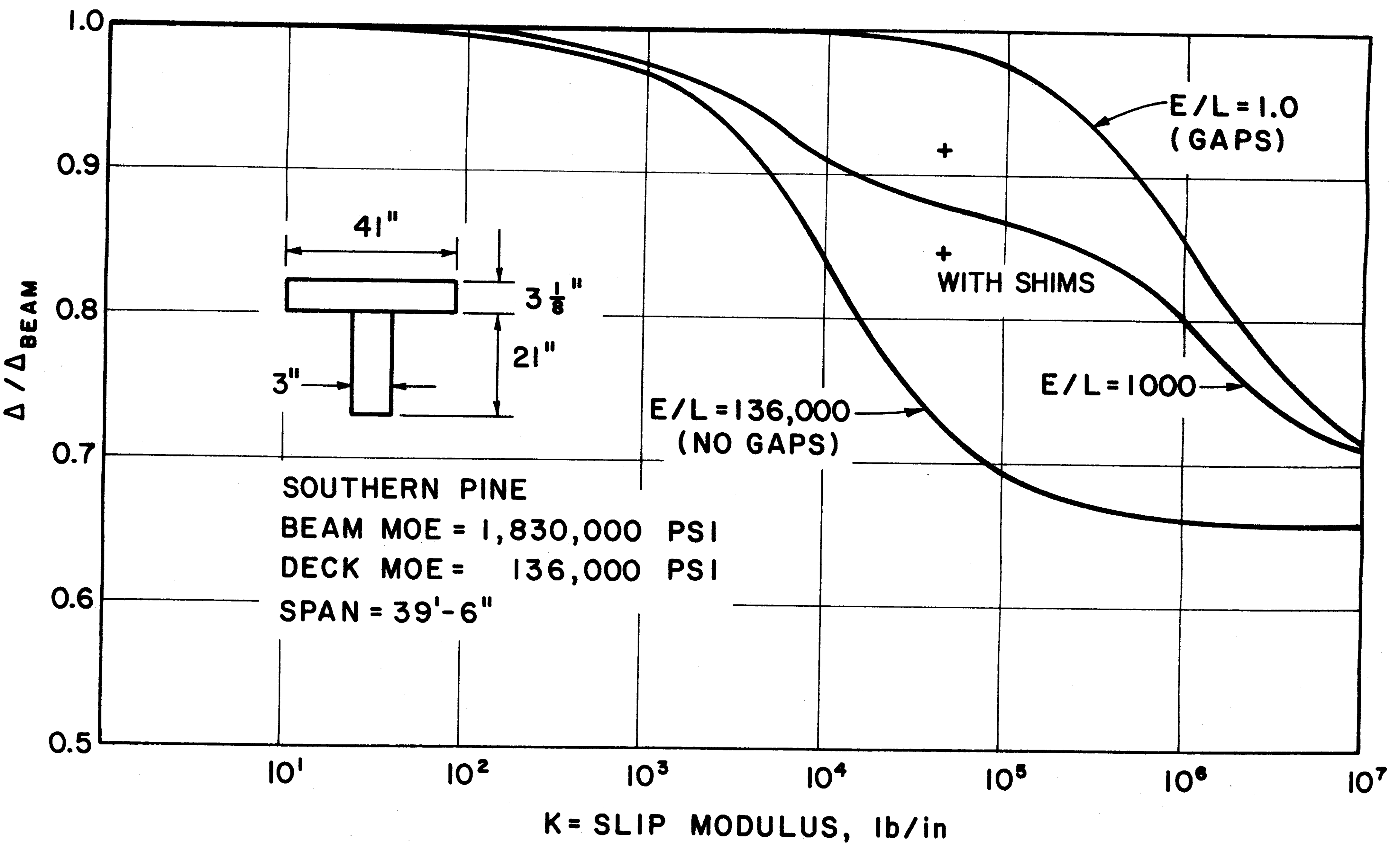


Figure 8. Composite Action Curve - Specimen SP-21

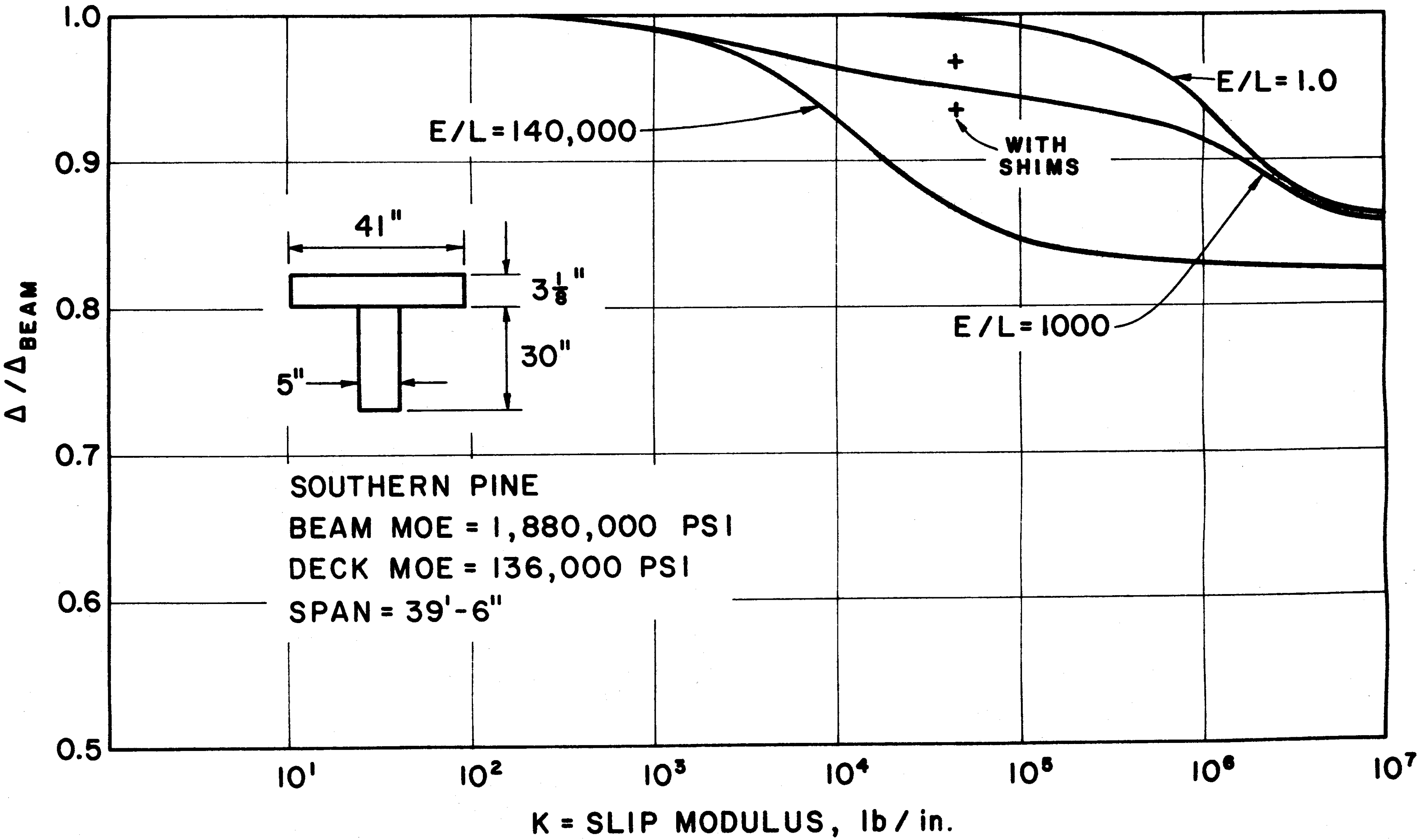


Figure 9. Composite Action Curve - Specimen SP-30

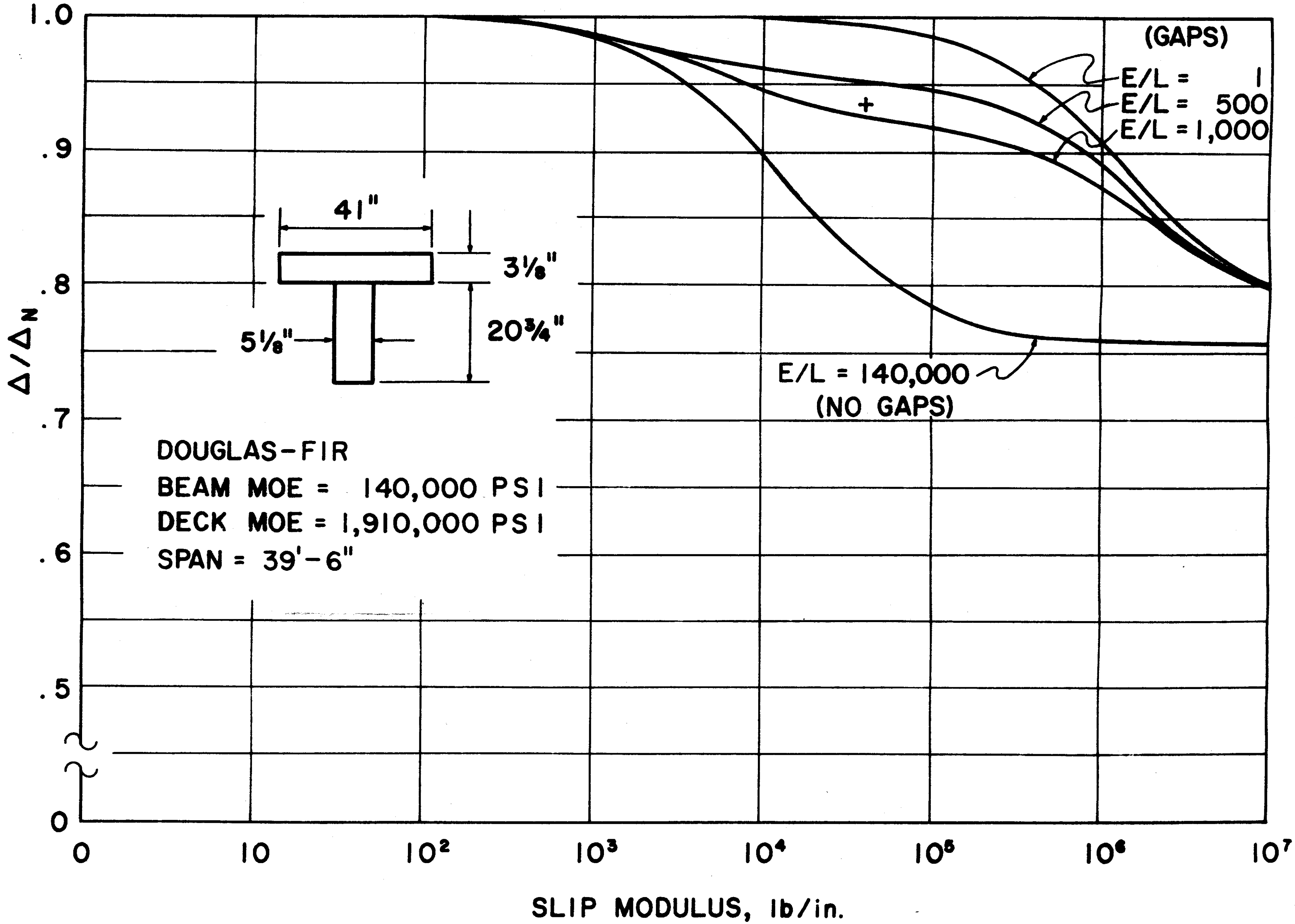


Figure 10. Composite Action Curve - Specimen DF-20.75

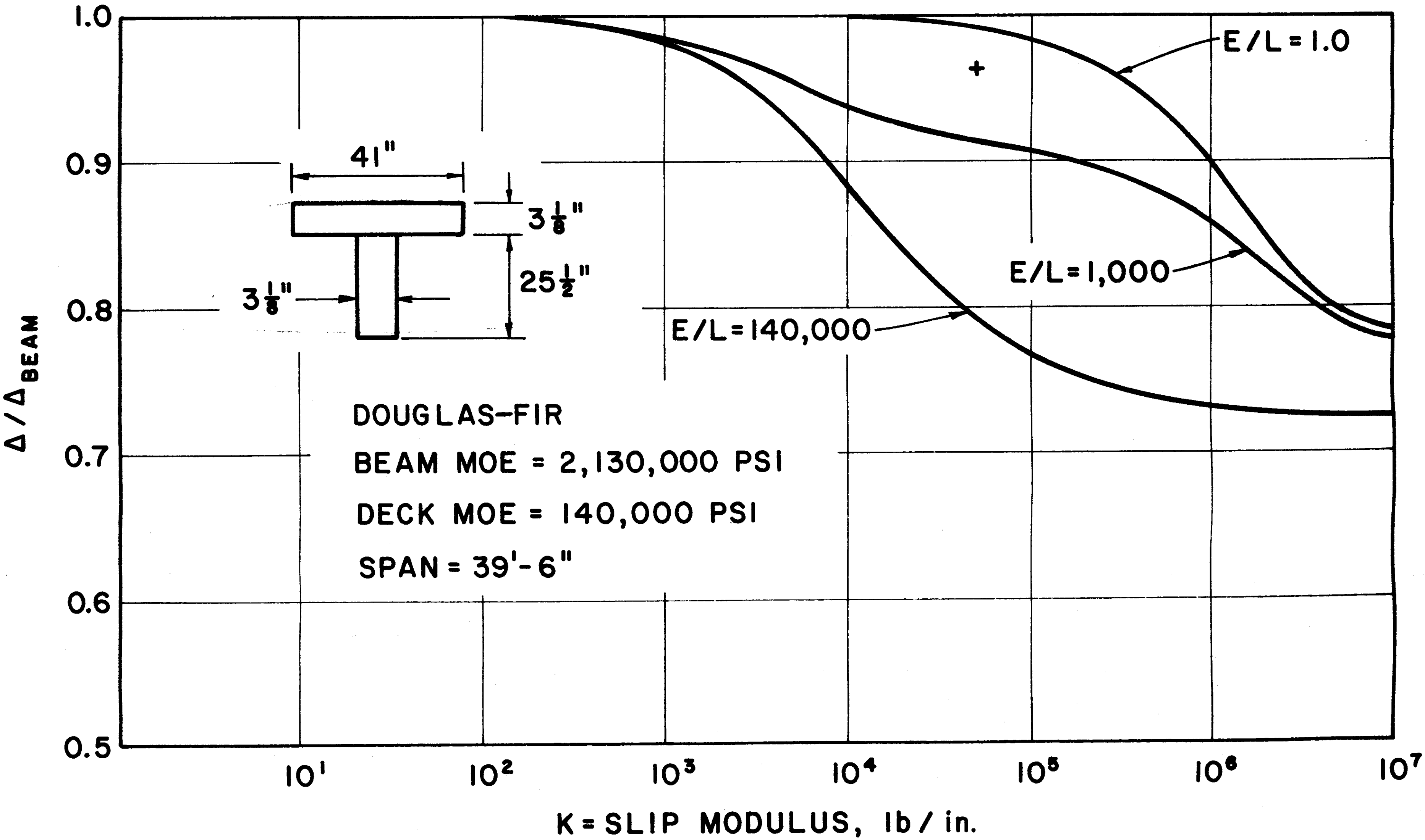


Figure 11. Composite Action Curve - Specimen DF-25.5

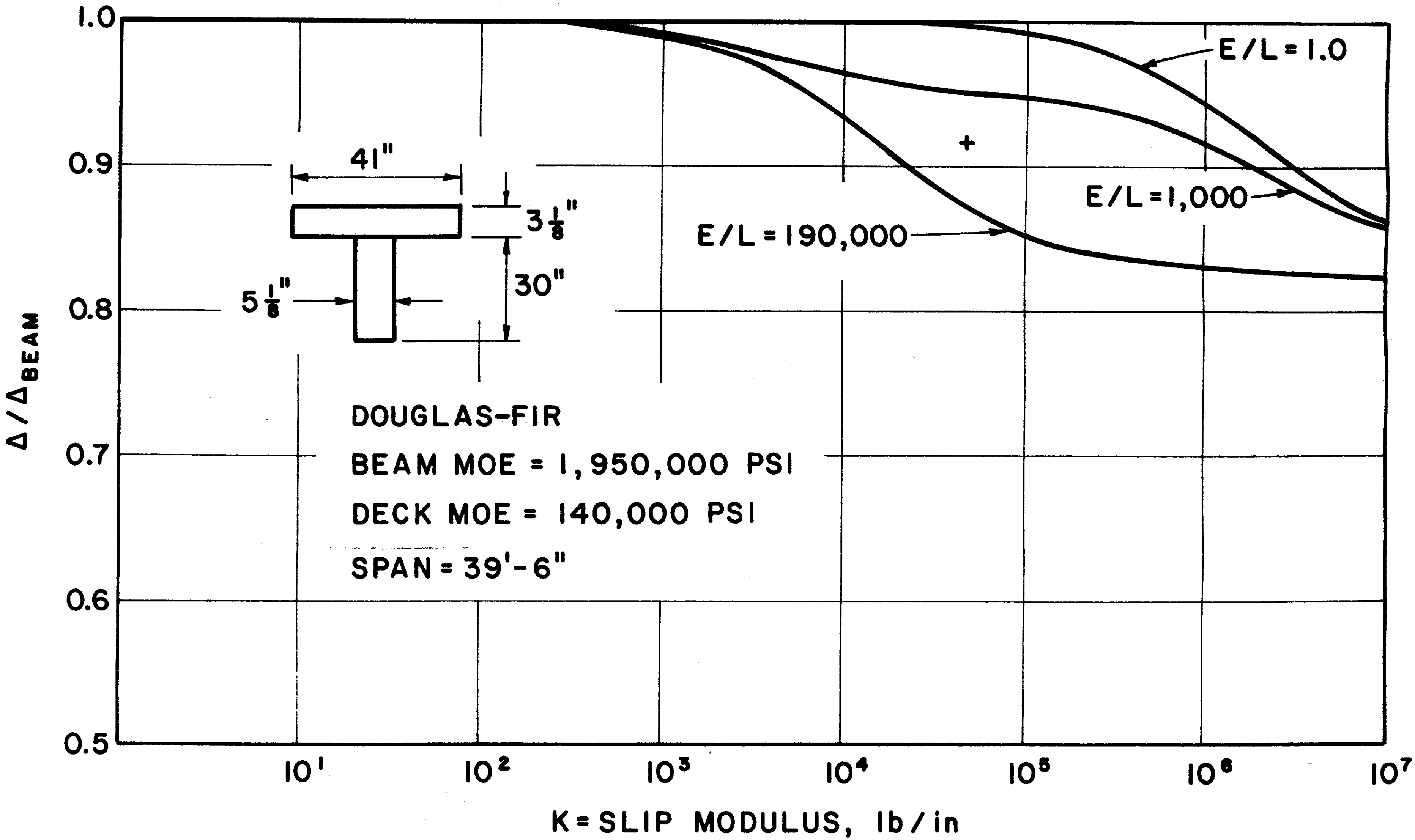


Figure 12. Composite Action Curve - Specimen DF-30

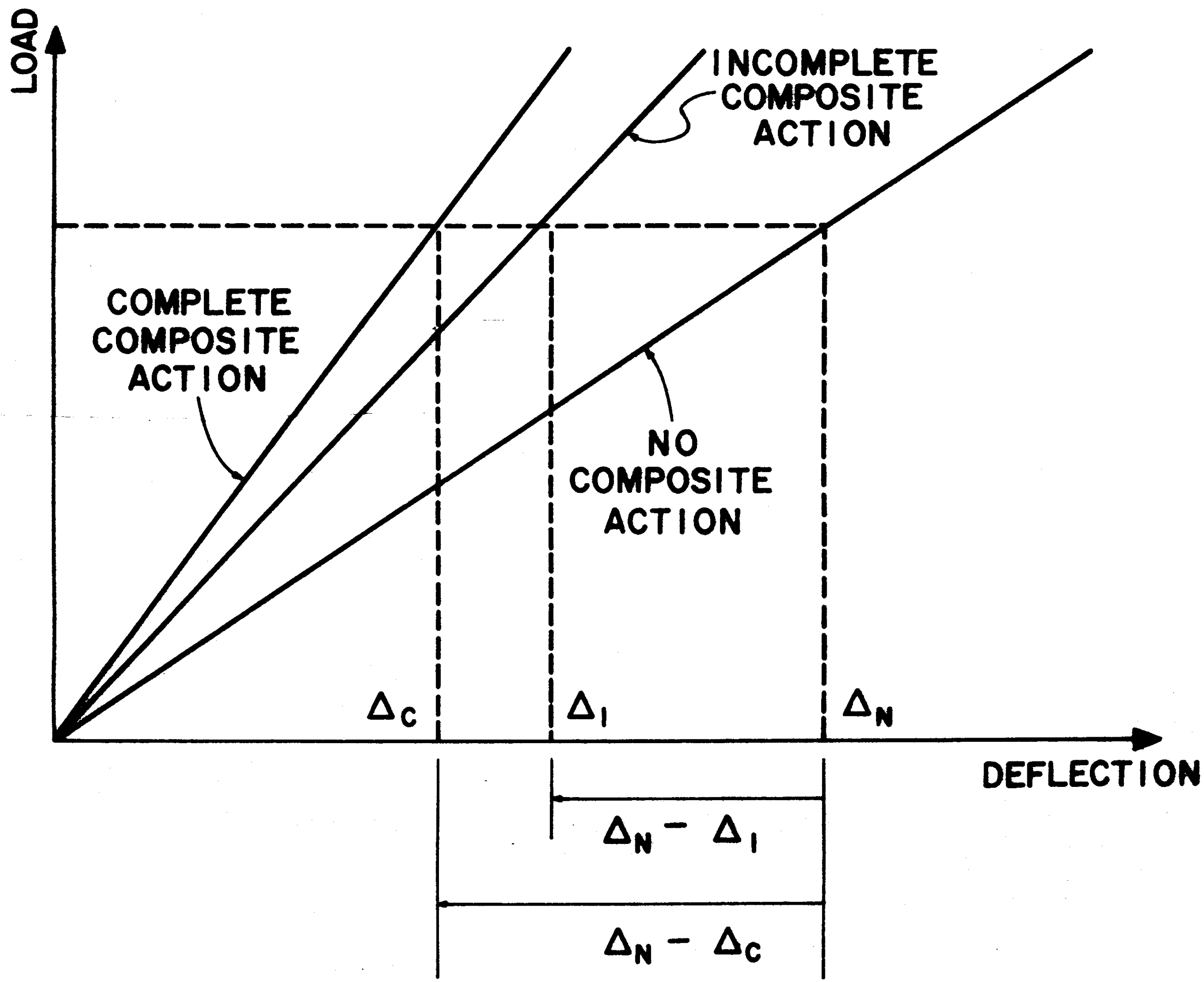


Figure 13. Effect of Composite Action on Deflection Behavior

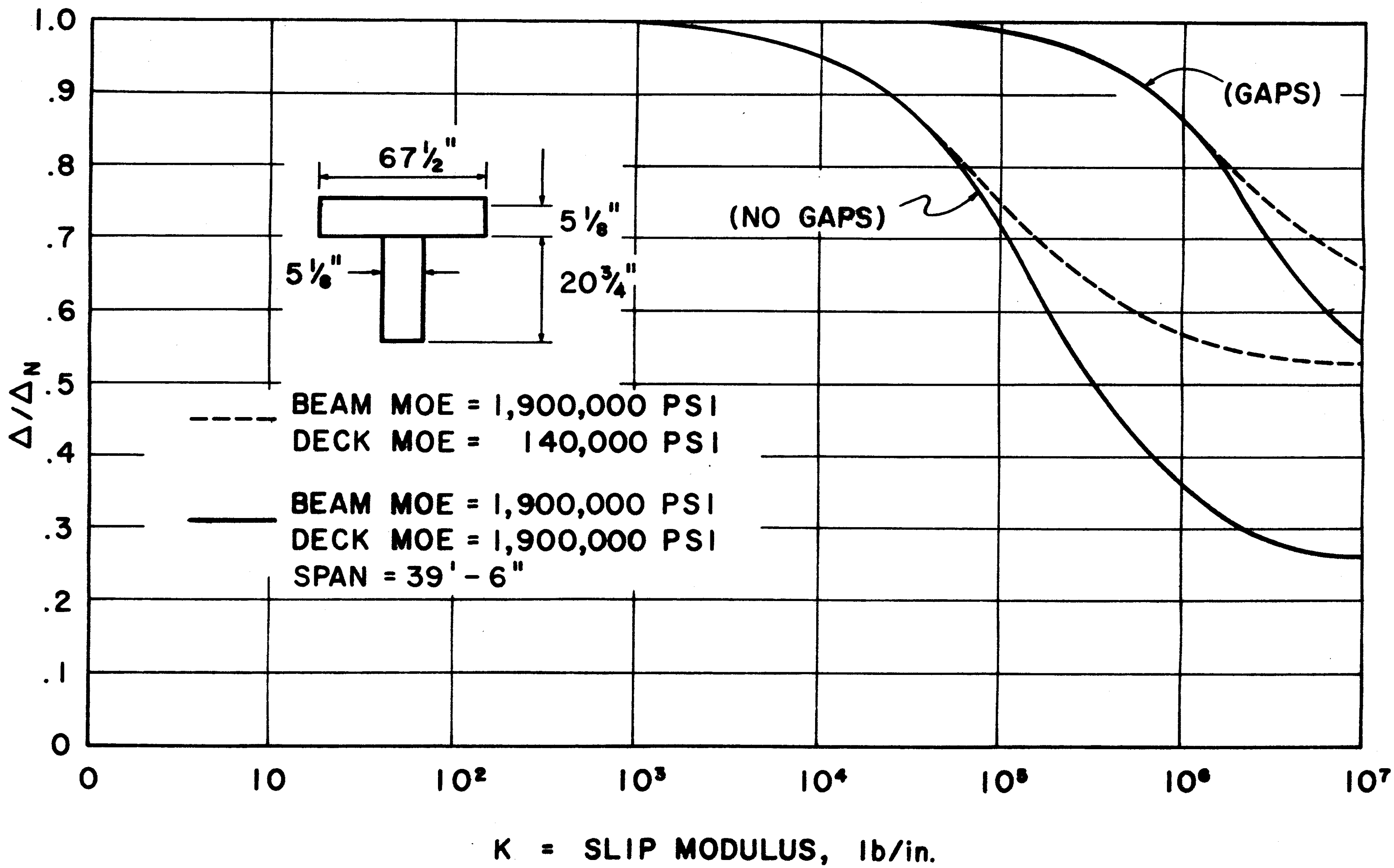


Figure 14. Composite Action Curve for Extrapolation Studies