Review of Alternate Load Factor (Autostress) Design

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Alternate load factor (Autostress) design is a limit-states design approach that was adopted by the American Association of State Highway and Transportation Officials (AASHTO) in 1986 in the form of a guide specification for the design of continuous steel-beam bridges using braced compact sections. The procedures recognize the inherent strength and ductility of continuous steel members and thus more closely approximate the way a continuous structure actually responds at higher load levels. As a result, a designer has more freedom to choose the distribution of material along the length of a member and thereby minimize fabrication costs. The procedures have evolved from a 15-yr progression of sponsored research. Presented in this summary paper is a brief overall historical review of all research to date on both compact and noncompact sections. Recent work has resulted in the development of a practical unified analysis approach that can be applied at all load levels. The approach is founded on classical indeterminate analysis theory and is readily amenable to computer programming. The current status of alternate load factor procedures is summarized. Several design applications are reviewed, and the potential for benefits in bridge rating is discussed. When eventually backed by sound quality software, these procedures may well usher in a new generation in steel-bridge design.

Research and development activities over the last two decades have resulted in a marked improvement in the understanding of the structural behavior of steel bridges. This improved understanding is reflected in successive editions of the design specifications, which are often based on more realistic behavior models.

For example, over the past 15 yr, the American Iron and Steel Institute (AISI) has been sponsoring a steel-bridge research program aimed primarily at developing improved design specifications that will reduce the total cost of straight steel rolled-beam and plate-girder bridges (*1*), which constitute 80 to 85 percent of the steel-bridge market. The program had a single concise objective: simplicity of completed structures to minimize total cost including fabrication.

The general approach used to accomplish the objective is to minimize the number of section changes in welded beams and girders by using prismatic members between field splices or changing the section between field splices only when dictated by available plate lengths. For rolled beams, the objective is satisfied by eliminating cover plates from interior-pier regions. The direction is not necessarily to reduce weight, but to distribute the material in the beam or girder to where it is most efficiently used to resist the load. Although there is usually some weight reduction, the cost savings resulting from overall simplicity in fabrication generally exceed the savings in material cost (*2,3*).

The inherent ductility of steel makes it possible to satisfy the basic objective without any external intervention. Limited local yielding under heavy loads at interior supports of continuous steel beams and girders causes excess pier moments to redistribute automatically to lightly loaded positive-moment regions. This internal shifting of moments as a result of local yielding occurs to some degree in all existing continuous steel beams and girders because of the presence of residual stresses locked into the member during manufacture and subsequent fabrication processes. Current design procedures do not adequately take advantage of this ability of steel to internally redistribute peak moments. Consequently, designers are often constrained by elastic moment envelopes. By recognizing this intrinsic benefit of steel and treating it more rationally in design specifications, designers have more freedom to choose the distribution of material along the length of the member to minimize fabrication costs.

The AISI research program resulted in the development of improved limit-state criteria that ensure that a continuous structure satisfies the same structural performance requirements as the present AASHTO limit-states approach known as load factor design (LFD) (*4*). The criteria permit a calculable amount of inelastic load redistribution in continuous-beam bridges at the two heaviest AASHTO load levels, overload and maximum load. To emphasize that all redistribution occurs automatically, the term "Autostress" was adopted for the new procedures (*5*). The procedures were eventually renamed alternate load factor design (ALFD), and were included in an AASHTO guide specification that was issued in 1986 for application to continuous steel bridges using either rolled or welded braced compact sections with a specified minimum yield strength less than or equal to 50 ksi (*6*).

HISTORICAL REVIEW

The AISI bridge research program started in the early 1970s with the idea that classical shakedown theory should be considered as a practical method of analysis of steel structures subjected to repeated loads (*7*). Shakedown analysis shows that for independently variable loads below the shakedown limit, permanent deformations caused by local yielding will eventually stabilize (*8*). After several loading cycles, the structure will respond elastically because of favorable residual stress patterns and moments (termed automoments) that are caused by local yielding. This phenomenon seemed well-suited to the

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development of rational limit-state criteria for continuous members at overload. The resistance of continuous members at maximum load is estimated by the well-established plastic-design principle of mechanism analysis (*8*).

Compact Sections

From these fundamental ideas, a design procedure for compact sections evolved and trial designs were completed in 1976 to determine the efficacy of the concepts (*9,10*).

The design procedure was gradually refined over the next few years on the basis of the results of several moment-rotation tests on component specimens (*11,12*). These compact unsymmetrical all-steel welded-beam specimens simulated the negative-moment region of continuous composite bridges between inflection points. The specimens were fabricated using steel with a specified minimum yield strength of 50 ksi. Each specimen was loaded well into the inelastic range to check compactness requirements, and to determine inelastic rotation-capacity requirements.

Two concerns were the effect of permanent deformations on concrete cracking over interior piers and on the fatigue life of the steel beams. Thus, a half-scale steel or concrete model of an interior-support region of a continuous composite bridge designed by inelastic procedures was tested in negative bending to

1. Demonstrate that the fatigue strength after inelastic rotation at overload meets the present AASHTO requirements;
2. Observe the amount, pattern, and width of concrete cracking;
3. Determine the number of cycles to shakedown; and
4. Observe steel-beam yielding during inelastic rotation (*13*).

The measured concrete crack width never exceeded 0.010 in. at any time during the test. When unloaded, the cracks closed to about 0.003 in. The maximum concrete crack width was the same at the overload moment currently permitted by LFD procedures, and at the largest overload moment that experimentally was possible without significant web and compression-flange buckling. At this larger overload moment, the total linear length of cracks had increased by 23 percent. However, the test specimen was shored during casting of the composite deck slab. For an unshored specimen, the amount of linear cracking at the LFD and maximum overload moments would be less than these amounts because the concrete strains would be lower. To control concrete cracking, the ALFD guide specification (*6*) requires that the overload stress in the reinforcing bars over interior piers be limited to the yield stress in the bar. It is also recommended that reinforcing steel with a specified minimum yield strength of 60 ksi be used. These steps control yielding of the reinforcement. Furthermore, the reinforcement must be distributed in accordance with AASHTO Article 8.16.8.4. Permanent deformations at overload are small and the yielding occurs primarily in the bottom (compression) flange; a complete plastic hinge is not formed. Thus, concrete cracking should not be substantially worse in bridges designed using ALFD procedures.

After being subjected to an inelastic rotation at overload about 30 percent greater than that permitted by LFD, the composite test specimen successfully resisted 5 percent more than the 2 million fatigue cycles required by AASHTO for a design stress range of 13 ksi. This design stress range applies to the critical details on the top flange at the shear studs and bearing stiffener (Category *C* details). It was also determined that the automoments that are formed in the beam do not affect the elastic stress ranges. ALFD designs must meet the established AASHTO Service Load limit-state criteria for fatigue and live-load deflection.

From the series of noncomposite and composite tests described above, the concept of an effective plastic moment was developed that could safely be used in a plastic mechanism analysis to better estimate the strength of compact continuous members at maximum load (*14*). The beam-line method, a convenient procedure developed for the analysis of non-linear building connections (*15*), was also demonstrated to be effective in computing inelastic rotations and automoments in continuous bridge members at overload (*16*).

The next step was to perform a field test of a bridge designed using these procedures. This goal was accomplished in 1982 with the design and testing of the Whitechuck River Bridge, a U.S. Forest Service bridge on a logging road in Washington state. This simple two-stringer, three-span continuous rolled-beam bridge was designed using steel with a specified minimum yield strength of 50 ksi. Cover plates were not used over interior piers because allowances were made in the design for automatic adjustments in the moments caused by local yielding. The bridge was statically load tested with heavy vehicles applied several times at critical locations. Shakedown was verified: the measured permanent deflections of the beams stabilized after a few applications of the test loads (*17*).

Because a continuous steel structure eventually shakes down, no limits on stress at interior piers are required. Stress limits are needed in positive bending, however, to control permanent deformations. Permanent deformations caused by yielding over interior supports may be included in the dead-load camber.

Finally, after further refinements in the design procedure, a specification for inelastic-design procedures for braced compact sections was developed, presented to AASHTO, and adopted as a guide specification in 1985 (*6*). A complete design example was included as an appendix to the guide specification.

Noncompact Sections

The next logical step was to investigate continuous composite bridges using noncompact sections, with more slender webs than allowed in the current guide specification. Exploratory moment-rotation tests in negative bending were conducted in 1984 on three noncompact unsymmetrical and symmetrical all-steel specimens with web-slenderness ratios of approximately 170 and compression-flange slenderness ratios of approximately 9.8. These slenderness ratios are roughly equal to the current AASHTO limiting values for transversely stiffened noncompact sections designed using 50-ksi steel by LFD procedures. Each specimen was transversely stiffened and was loaded well into the inelastic range. A curve representing the lower bound of the descending branches of the three test moment-rotation curves was developed (*18*).

At the same time, noncompact composite (steel-concrete) specimens with web-slenderness ratios varying from 120 to 165 were tested in positive bending to determine their maximum capacities and plastic-rotation behavior (*19*). These tests showed that composite sections in positive bending have no trouble achieving their plastic-moment capacity, as long as the concrete slab is prevented from crushing, because the majority of the web is in tension. However, plastic rotations do occur as these sections approach the plastic moment, which will increase the moments and plastic rotations at adjacent piers (*16*).

In 1982, the AISI and the Federal Highway Administration (FHWA) began a 6-yr joint research project involving the testing of a model bridge designed with inelastic procedures using noncompact plate-girder sections. The bridge represented a 0.4-scale model of a 2-span continuous prototype with 140-ft spans, and included modular precast deck panels that were transversely and longitudinally prestressed (*20*). The prototype design used steel with a specified minimum yield strength of 50 ksi. Because inelastic-design procedures were used, there were no flange transitions required in the field section over the interior pier. The tests that were conducted on the model confirmed that shakedown with the formation of automoments occurs, and also illustrated the tremendous reserve strength available in continuous steel bridges beyond first yield that is not adequately taken advantage of in current design procedures.

In 1988, three additional moment-rotation tests in negative bending were conducted on symmetrical all-steel specimens with web-slenderness ratios varying from about 90 to 165 (*21*). They differed from previous tests in that stockier compression flanges (with a slenderness ratio of approximately 7.0) were used along with transverse stiffeners placed at a close spacing of approximately half the web depth on each side of the center bearing stiffener. The stiffeners were on one side of the web and were welded to the compression flange. The combination of the stockier compression flanges and closely spaced transverse stiffeners resulted in improvements in the inelastic-rotation capacity at relatively low cost. The benefits of stockier compression flanges were also noted in similar tests that were recently conducted in Sweden (*22*).

An additional composite (steel-concrete) specimen, representing the interior-pier region of a prototype continuous girder with 200-ft spans designed using inelastic procedures, was tested in early 1991 at the University of Texas at Austin. The web slenderness of the specimen was approximately 175, and the compression-flange slenderness was approximately 7.4. Closely spaced stiffeners were included adjacent to the center bearing stiffener. Finally, an investigation started at Cornell University and now in progress at Purdue University is developing analytical methods for obtaining the moment-rotation curves (*23*).

From the results of the 1988 tests, empirical unloading curves were developed that vary with the web-slenderness ratio. These curves may be used directly in a new analytical method that was developed in 1989 (*24*). The method provides a unified analysis approach at the AASHTO service load, overload, and maximum load levels, and accounts for yielding at any number of locations throughout the span. The method is founded on classical indeterminate analysis theory, is readily adaptable to computer programming (including three-dimensional finite-element analysis), and is easier to apply for bridges with more than two continuous spans. The method gives the same results as the beam-line analysis at overload, and more accurate results than the mechanism analysis at maximum load.

Trial designs for symmetrical two- and three-span continuous bridges with spans varying from 100 to 300 ft were made using the empirical moment-rotation curves in combination with the unified analysis method. The studies showed that material savings up to about 15 percent were attainable by using smaller sections at interior piers than permitted by LFD procedures (*24*). Significant savings in fabrication costs should also be possible. Moreover, the designs demonstrated the tremendous flexibility available to the designer.

CURRENT STATUS

Application to Design

The first application of the AASHTO guide specification (*6*) was the Seeley Creek Bridge outside Elmira, New York, designed by the New York Department of Transportation (DOT). This three-span continuous rolled-beam bridge, with a 104-ft center span and 83-ft end spans, weighed 27.4 psf. A single rolled section was used for all beams; cover plates were not required over interior piers to satisfy the limit states (*25*).

The state of Tennessee has constructed two rolled-beam bridges without cover plates using the guide specification provisions: the four-span continuous Big Opossum Creek Bridge with 111-ft center spans and 83-ft end spans (22.5 psf), and the four-span continuous Route 42 Bridge over the Wolf River with 128-ft center spans and 101-ft end spans (25.3 psf). For the Wolf River Bridge, the average bid price for the structural steel was approximately 30 percent less than that for a comparable bridge designed by LFD procedures that bid 2 months later (*3*). Tennessee is also considering using the guide specification to design two additional structures. They have found that these designs are highly desirable for shorter-span bridges at remote sites where transportation of long heavy beams is restricted, and at high crossing sites where erection is difficult.

The state of Maine has recently completed the design of the first ALFD bridge using compact welded beams. The three-span continuous East Outlet Bridge has a 124-ft center span and 103-ft end spans. The bridge weighs approximately 25 psf and uses prismatic steel sections along its entire length. It was estimated that fabrication cost savings of up to 10 percent were realized over a traditional load factor design (*26*).

The state of Illinois has completed the construction of the two-span continuous (62.75 ft-52.75 ft) St. Clair County Bridge on State Route 163 designed by ALFD procedures. Two rolled sections were used without cover plates. Also, the state of Oklahoma has prepared alternate designs for two small rolled-beam bridges designed using ALFD procedures to be bid competitively against prestressed concrete.

A misconception has traditionally existed that ALFD procedures are only applicable for rolled-beam design. As demonstrated by the state of Maine design, in some instances, an ALFD using compact welded beams may be the most economical steel design for a typical short-span bridge (*2*). Welded beams make it easier to meet established live-load deflection criteria. ALFD procedures do not necessarily encourage minimum weight design. In many instances, short-span bridges designed by ALFD procedures are as heavy or nearly as heavy as load factor designs. In ALFD, the material is distributed where it is more efficient. The primary purposes of ALFD procedures are a minimum cost and better design accomplished by simplifying fabrication and by eliminating details with undesirable fatigue characteristics.

Application to Rating

Perhaps the biggest benefit that might be realized from the application of Autostress theory is in the area of bridge rating. By applying inelastic procedures to rating, it may be possible to significantly upgrade the posted load-carrying capacity of many continuous steel bridges. Some progress has been made in this area and potential benefits have been illustrated (*27,28*)

Software

ALFD procedures are computationally more intensive than current design procedures, particularly for bridges with more than two spans. However, the procedures are well-suited to computerization, especially when employing the unified analysis approach. One software vendor has made progress in the development of commercial computer software that applies the beam-line and mechanism analyses recommended in the current guide specification. The availability of computer software should increase the potential for application of the ALFD procedures.

SUMMARY

Alternate load factor (Autostress) design is a limit-states design approach that attempts to close the gap between design assumptions and actual behavior by introducing inelastic-design concepts. The limit-state criteria introduced in ALFD allow designers more freedom in proportioning members, and remove unnecessary constraints imposed when trying to design for elastic moment envelopes. Steel bridges are not elastic at higher load levels, but possess high ductility. Controlled local yielding of a continuous steel beam at higher load levels results in beneficial redistribution of the elastic moments from negative- to positive-bending sections. As a result, simplification of fabrication can be accomplished to help minimize costs. ALFD procedures should prove particularly beneficial in bridge rating.

ALFD procedures were developed as a result of research studies over the last 15 yr. Research has been conducted on both noncomposite and composite component specimens, a scale model bridge, and an actual bridge, designed using both compact and noncompact sections. The procedures have been demonstrated to adequately satisfy all related performance criteria. Recent research has culminated in the development of a new unified method of analysis to determine the actual moments and plastic rotations in continuous beams. The method shows great promise because the same analysis method can be applied at all load levels. The method is founded on classical indeterminate analysis theory and is readily adaptable to computer programming. Present moment-rotation curves can be used in the analysis, but additional curves are desirable.

ALFD procedures have been available for use since 1986 in an AASHTO guide specification for steel-beam bridges using braced compact sections fabricated from steels with a specified minimum yield strength less than or equal to 50 ksi. Several economical short-span continuous bridges designed by the guide specification provisions have been constructed. Both rolled- and welded-beam sections may be used; however, compact welded beams may be the more economical solution in many instances. Usage of the guide specification should increase as computer programs are developed. To further assist designers, a new chapter is being prepared for the *AISC Marketing Highway Structures Design Handbook* (*29*). The chapter will include a step-by-step design example of a three-span continuous bridge designed by ALFD procedures. The guide specification provisions have also been incorporated in the draft load and resistance factor design (LRFD) specification being prepared for AASHTO (*30*). The procedures are given as an option for continuous steel beams using compact sections that meet specific slenderness and lateral-bracing requirements.

It should soon be possible to develop inelastic-design provisions for continuous steel bridges using noncompact sections. The potential for significant material and cost savings is evident. Backed up by good-quality computer software, these procedures could eventually represent a new generation of steel-bridge design.

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