Economical Construction Practices Inseparable from Structure Design

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This paper develops the thesis that modern technology has made available new and improved materials, equipment, and techniques that can contribute substantially to more economical construction of bridges. It discusses briefly the several categories in which outstanding advances have been made. It further develops the idea that the fullest advantage of economics inherent to these technological advances cannot be realized unless the designer is fully aware of them and creates structure design which permits their incorporation.

The paper avoids the use of examples, which reflect only the ideas of an individual designer, by emphasizing the fields and categories in which the advances have been made. It discusses the economies that can be achieved by a designer with a complete awareness of shop practices in fabricating plants, form building processes and devices, falsework types available, welding equipment and new materials.

It also emphasizes that any of the technological advances may be nullified by a designer who creates plans and writes specifications that inhibit their use.

• NEVER BEFORE has there been available to the structural designer and contractor such a vast reservoir of tools for more economical construction. These tools include new and better materials, new and improved techniques both in fabrication and construction, larger capacity handling equipment, and better form and falsework devices.

The full potential for economy resulting from these technological advances cannot be achieved, however, unless the designer is aware of, and uses, them. Construction and fabrication details indicated on plans must permit efficient use of the tools available to both fabricator and contractor. The use of specifications written for an earlier period when these means were not available often denies the contractor opportunity to exercise any initiative. Special provisions and plan notes are often so restrictive that real economy cannot be achieved. Only the designer can mobilize all the available tools in such fashion that they can combine to produce maximum economy.

This paper only attempts to discuss the several categories in which advances have been made. It merely generalizes the economic advantage that can be achieved by a designer who is acutely aware of the potential economy of designs that permit the maximum efficient use of new materials, construction methods, and equipment. Specific details, which reflect only an individual designer's preference, will be avoided.

STEELS

During the recent decade, the steel industry has made outstanding progress in the development of new steels. Some have generally improved mechanical properties and chemical compositions, and others are formulations having desirable characteristics for specific purposes. The designer must be aware of all these available new materials, their prices, and their advantages and disadvantages from a fabrication and construction standpoint.

Structural carbon ASTM A-7 steel has long been the most common grade used in bridge construction. It commands no premium in price and is still the most common grade used in main members and practically all secondary members where minumum section, size, and thickness specifications govern. The fact that the chemical requirements for A-7 steel do not provide a maximum carbon content limits its use in welded structures. However, a review of chemical analyses show that 95 percent or more of A-7 steel actually falls into the range of composition specified for weldability. The careful designer will make detailed design comparisons, both economic and functional, to justify the use of the premium steels.

Structural steel for welding, ASTM A-373, was developed to meet the demand for a weldable steel for bridge main members. It has given impetus to greater use of welded girders in place of large wide-flange shapes. It commands a modest price premium, but the saving in weight resulting from simpler welded details and fabrication economies more than offset this premium.

Structural steel ASTM A-36 steel is potentially the most useful of the recent steel developments. Its physical characteristics are improved by approximately 10 percent above A-7 steel and with a cost increase of only $1.00 per ton it produces real economy in bridge construction. However, this advantage has been denied to designers of Federal-aid bridge projects involving welded members by a controversy over the weldability of the A-36 grade. The majority of user organizations consider it to be fully weldable when proper procedures are used. A minority, which includes the Bureau of Public Roads, has rejected its use in welded bridges except as cover plates not exceeding 1 in. welded to rolled girder shapes.

The new high-strength structural steels ASTM A-440 and ASTM A-441 steels are most economical materials which have resulted in the extension of the economic range of welded plate girders well into the span lengths that were formerly considered appropriate only to trusses. Girders in the 200- to 350-ft range are now commonplace and permit the added advantage of unlimited vertical clearance for relatively long span structures. The higher price of these steels is more than offset by the reduction in weight resulting from their higher allowable design stresses. The costs are now so well-established by common usage that economic comparisons can be accurately made to establish the sections of trusses or girders that can profitably employ the higher strength, higher priced steels.

Still higher strength steels are available in special quenched and tempered grades. The best known of these, commonly called T-1 steel, is available for use, usually in high-stressed members of long-span trusses; its economy can be readily established by careful analysis and cost comparisons. Outstanding examples of the use of this material are the new Carquinez Strait bridge and the Benecia-Martinez bridge in California. A 100,000-psi yield strength steel is being used experimentally in pilot projects in Iowa involving the prestressing of steel girders. The economy of this plan would seem to hinge on the development of fabrication techniques. The principle is sound and designers should watch this development carefully.

Steel Fabrication and Erection

Fabricating plants are accustomed to working with structural sections rolled to tolerances adopted by the steel industry and to fabricating requirements, either welding or bolting and/or riveting, in conformity with AWS or AISC specifications. If a designer, by plan note or special provisions, requires more precise measurements, smaller tolerances or more restrictive methods, an additional charge is justified and some economy is sacrificed. Constant liaison with fabricators is desirable in order to know which details and operations are proving costly. Usually modifications of these details can affect economics at no sacrifice to the functional excellence of the design.

Heavier handling equipment and the ability to transport long loads, either on multiple railroad cars or by truck and trailer, enable the designer to provide for members of greater length to be fabricated in the shop with lower fabrication costs. Fewer field splices reduce the erection costs by reducing falsework requirements and the number of costly field connections, either riveted, bolted or welded. The erector may often furnish valuable suggestions as to modifications of the next design, which might result in more economical erection. For example, bracing frames can be designed to be fabricated in the shop and shipped as assemblies instead of individual members to be interconnected in the field.

A fertile field for economy is the duplication of members and details. Careful design, especially of handrail members, joists, panel lengths and cross-bracing frames may result in repetition of details that will affect reduced fabrication costs.

Techniques have been developed for continuous welding of plate girders which enable designers to use fabricated girders at a lower total cost than rolled sections of the same section modulus, by taking advantage of the more efficient distribution of metal. Carbon dioxide welding is showing great promise as an economical technique. Button welds connecting thin plates in secondary details may cut costs in the shop.

The merits of composite steel and concrete construction are so well-established as to need no mention. However, the type and method of fastening shear connectors influences economy of this construction also. The development of the automatically welded stud has reduced the "time in shop" sufficiently to show a net reduction in costs in most shops.

Hybrid steel girder design, using webs of lower strength steel and flanges of higher strength steel, offers promise of being an important step forward in economic design of girders. The design principle is valid, and testing already completed supports the design assumptions. However, the public agencies that must approve such designs are, as always, slow to accept anything new and final acceptance of the hybrid girder design probably hinges on wider acceptance of plastic or ultimate strength design for dynamically loaded structures and on further test data in fatigue strength of such girders.

Reinforcing Steel

The recent development of new, higher strength and large-diameter bars is a tool that will become more useful to the designer as wider acceptance is achieved.

The A-432 reinforcement bars are available at prices competitive with A-15. They will permit wider bar spacing and less steel or smaller concrete sections, all of which may result in economy. The wider spacing results in an economy by handling fewer bars and by easier pouring of concrete into forms and around the reinforcement. A-431 bars command a premium but may also prove economical as in the case of the A-432 bars. With either of these reinforcements economy dictates the use of 4,000-psi, or stronger, concrete. However, because such concrete is already in use in most States and concrete to 5,000 psi is easily and economically produced, this requirement poses no problem.

The king-size 14 S and 18 S bars have a distinct place in economical design. They can be utilized more easily and more satisfactorily than bundled bars which have been utilized with some success by a few designers. They are also quite useful in heavy frames, usually foundation elements.

CONCRETE

Cements, aggregates, additives, controls, and mixing and placing techniques have all been improved to such an extent that reliable 4,000-psi, and stronger, concretes can be custom-produced with negligible additional cost. When it suits his purpose, the designer need feel no hesitancy in specifying high-strength concretes, keeping in mind only the benefits obtained compared to the added costs incurred.

Lightweight aggregates now available commonly produce concrete in the 4,000 to 5,000-psi range with weights of 96 to 110 pcf. They usually cost substantially more per cubic yard in place, but the saving in materials in supporting members may justify its use in bridge floors.

Awkward, small-area pouring sequences formerly required for continuous span floors are costly operations. Larger mixing, pouring, and finishing capacities combined with judicious use of retarder additives often permit continuous pours with resulting economy.

Prestressed concrete construction is so well-established and so widely used that the designer need only know the comparative costs of prestressed structures and the alternative type of structure to make a proper economic selection. Because the industry has developed standard methods and shapes, much as in the case of the steel industry, it is incumbent on the designer to recognize these standards, especially when pre-tensioning is desired. More latitude is available when post-tensioning is desirable or permitted. Maximum economy usually results when only the tensioning forces are specified and the contractor is afforded the option of pre-tension or post-tension methods.

BEARINGS AND EXPANSION DEVICES

Bearings and expansion devices are the "jewelry" of the steel industry. There are more types and less uniformity in these details than in any other element of bridge construction and their cost in many cases is out of line with the value of the function performed. Fortunately, this situation is being bettered by use of comparatively recent developments.

Elastomeric-bearing pads give promise of more economy for bearings for relatively short-span bridges. They permit both movement and rotation of the span. Elastomer joint fillers are available which improve the sealing and riding qualities of joints between short spans.

The development of oil-impregnated bronze bearings has extended the length of the span that can be carried on sliding plates. However, the very long spans must continue to use combinations of rollers or pins and rockers that are very expensive to produce.

FORMS AND FALSEWORK

Form costs are a major item and the designer must keep in mind three questions and their answers in designing concrete details: (a) how will the form be built; (b) how will it be removed; and (c) can it be used more than once? A concrete design for which it is simple to make or procure forms that can be stripped without damage and re-used in the structure lends itself to maximum economy.

Metal and fiber forms are commercially available for column and floor unit sections. Although designs should not be made for use of any specific form, it is only good judgment to keep column sizes and floor spans and panels in dimensions that permit the contractor the option of building such forms himself or buying or renting them.

CONCLUSION

This paper has discussed a few, but by no means all, of the available means that the careful designer will consciously consider to attain his goal of economical construction. The attributes, over and above technical competence, that distinguish the master in his field from the merely adequate craftsman included the following:

1. Awareness and imaginative use of new materials, methods and machinery.
2. Familiarity with fabrication and construction procedures and a willingness to adapt designs to proven economical techniques.

Finally, it cannot be too strongly emphasized that the finest materials available, the improved techniques developed, and the contractors know-how on the job can be mobilized for the attainment of excellence and economy only by the design engineer with awareness, initiative, and imagination.

Discussion

M. G. SPANGLER, Research Professor of Civil Engineering, Iowa State University, Ames—The author has presented a powerful and convincing argument in favor of closer and more intimate liaison between those phases of the production of a finished structure usually labeled "design" and "construction." The writer is in complete agreement with his thesis and wishes to offer a few experiences that lead to the same conclusion. If one may think of design and construction as the right and left hands of an engineering organization, here is a perfect example of the need for the right hand to know what the left hand is doing, and for the left hand to know and understand the reasons for what the right hand has done.

The writer's opportunities for observation of construction have been primarily in the field of underground conduits, such as sewers, culverts, and similar structures. On occasion, the lack of coordination between those who designed the structure and those responsible for its construction according to the plans and specifications has been appalling. In the fall of 1960 there was a great deal of talk about the "missile gap" during the presidential campaign, although it now appears that such a gap did not really exist or at least has closed very rapidly. The gap between engineering design and construction is, in many cases, much wider than the so-called missile gap, even at its widest point as proclaimed by the uninformed, and this gap is closing very slowly, if at all.

The lack of coordination between design and construction probably can best be described by citing some specific examples. These examples are real and not imaginary.

Several years ago in one of the provinces of Canada, a newly constructed storm sewer experienced extensive structural failure of pipelines 18 and 20 in. in diameter. Too often, and it was true in this case, when failures of this kind occur, the resident engineer comes out with a statement that the pipes were no good. This readiness on the part of engineers to attack the quality of the material used on his project is always somewhat puzzling because he is, in reality, condemning his own engineering service. It is the duty of the engineer in charge of construction to see to it that the materials furnished are of acceptable, specified quality. In the field of underground conduits there are plenty of tests the engineer can perform to insure good quality.

When such an accusation is made, the pipe manufacturer is put on the defensive. If he has faith in the quality of his product, he is on the horns of a dilemma; whether to counter such a claim and thereby possibly alienate the good will of a valued customer or tacitly to accept blame for the failure and possibly keep the customer's good will and sell him more pipe in the future.

In this case, the pipe manufacturer decided to resist the claim that the pipe was faulty. The writer was asked to investigate the cause of the failure. Examination of the plans and specifications and tests of the quality of the pipes indicated that they should not have failed if they had been installed according to these documents. In an interview, the resident engineer stated emphatically that the pipes had been installed on the specified Class B bedding and that the width of trench did not exceed that specified. The quality of bedding and the width of trench are vital elements in the structural performance of a sewer line.

Next, the contractor's foreman who had installed the pipe was interviewed out on the job. He described the method of bedding the pipes and his description fell far short of the high-quality procedure required to obtain a Class B bedding. He was then asked about the width of trench in which the pipes were laid. He stated that a back hoe was used for the excavation and pointed to a machine standing about one-half block away. When the width of the bucket was measured, it was found to be 4 in. wider than the maximum ditch width allowed by the specifications. The foreman expressed the opinion that in all probability the actual width of trench was somewhat greater than the width of the bucket. To verify this, a trench was dug at right angles to the pipeline down to the top of the failed pipe. The planes of contact between the backfill soil and the sides of the original trench were easily identified. A measurement indicated that the actual trench was at least 6 in. greater than that specified.

A quick calculation using the actual ditch width and the probable type of bedding obtained, as described by the foreman, indicated that failure of the pipeline was inevitable. It was simply overloaded by a wide margin. If it had been constructed in the manner specified, it would undoubtedly have carried the load without difficulty. This was a clear-cut case of poor coordination between design and construction and a lack of understanding of the importance of certain details of the design. The result was a very costly failure of what should have been a successful structure.

In another situation in a Midwestern State about ¼ mi of 20-in. sewer pipe failed during construction, and the contractor was required to reconstruct the line. An investigation revealed that the going was quite wet in this location. The contractor elected to use a shield in the bottom of the trench to protect workmen during pipe laying operations, and to reduce the amount of excavation. The shield was a steel structure with parallel vertical sides which were 5 ft apart, out-to-out. This dimension established the width of the ditch at the level of the top of the pipe and was much greater than the width permitted by the specifications. Calculations indicated that if the specified ditch width had been adhered to, the pipes would have carried the load safely, but with a shield as wide as the one used, the pipes were seriously overloaded and the failure could be accounted for readily.

The investigation revealed that the consulting engineer who had designed this project had a resident inspector on the job at all times during construction. The inspector did not at any time call the attention of the contractor to the fact that his ditch was too wide and that trouble might later develop because of this fact. He remained completely silent relative to this gross violation of the specifications. When questioned about this matter, he stated that he did not wish to tell the contractor how to do his job. The writer is not a lawyer, and does not pretend to know where legal responsibility resides in a case like this, although the contractor probably had to pay the bill for reconstruction of the line. However, the engineer had a moral obligation to guide the contractor and control the construction in accordance with the plans he had prepared. His failure to do so constituted a gross violation of his responsibility. Another clear-cut case of poor coordination between design and construction, in spite of the fact that the designing engineer and the engineer in charge of construction were one and the same person.

Several years ago the writer served on a task force that prepared Chapter IX on Structural Requirements of the American Society of Civil Engineers Manual of Practice No. 37 (Water Pollution Control Federation Manual No. 9) on Design and Construction of Sanitary and Storm Sewers. When the factor of safety for sewer design was under discussion, there were, as might be expected, wide differences of opinion as to a suitable factor of safety to recommend. One very competent engineer from the sewer design department of a major Midwestern city argued very strongly for a factor of safety that some members of the task force considered to be excessively high and uneconomical.

The reason advanced by this engineer in support of a high factor of safety was that in his city the sewer design department and the sewer construction department were entirely independent of each other. He stated that no matter how well-executed a design might be, when the plans were turned over to the construction department there was no assurance that the specified design details would be adhered to. Therefore, a relatively high factor of safety was necessary.

Such a lack of coordination between design and construction is indefensible. An administrative officer who permits such a lack of intercommunication is extremely unwise. The public is entitled to protection from the potentially costly results which may accrue from a situation such as this.

There are times when highway department construction forces are given too much leeway to change plans of structures without consultation with designers. Some years ago, a monolithic arch culvert design called for a break in the grade of the flow line to meet the conditions imposed by a cutting stream bed. The design provided for a steep grade in the upper two-thirds of length and then a flat grade to the outlet. The structure as designed had a break in grade which was concave downward in relation to a straight line from inlet to outlet. This design required a considerable, though not excessive, amount of excavation.

When it came to construction, the resident engineer decided to save some excavation and reversed the situation by flattening the grade in the upstream portion and steepening it at the downstream end, making the grade concave upward. This decision, made without consultation with the design department, resulted in two adverse features in the completed structure. First, the exit velocity of the effluent water was greatly increased, creating potentially dangerous scouring velocities below the culvert. Second, the site was located in a region where subsidence of the natural ground under the weight of an embankment was unusually great. This latter situation caused the culvert to settle a relatively large amount. Because of the concave upward conformation of the barrel, very high compressive stresses were generated at the junction of the upstream flat section and the downstream sloped section as this settlement developed. These compressive stresses were sufficient to crush the concrete in the crown of the arch at this junction.

Still another decision that was made in the field without consultation with designers was to permit end dumping of about the first 15 ft of the embankment material. This caused lateral forces to be exerted against the culvert and it was displaced laterally about 1 ft in the central region of the barrel. This lateral displacement caused the sides of grooves of the tongue and groove joints in the barrel to shear off, creating open joints for potential infiltration of soil.

This culvert is continuing to fulfill its function as a passageway for water under the highway embankment, but it is not as good a structure as the public paid for, and not as good as it might have been if there had been closer coordination between those who designed it and those who supervised its construction.

These examples have been few in number, but similar observations could be multiplied many-fold. There is a need for improvement in liaison between design and construction and a closing of the gap between these two important facets of engineering practice. Chief engineers and other administrative officers of engineering organizations; State highway departments; city and county public works dpeartments; and consulting engineers in private practice—all need to take a look at their respective organizations and be sure that the right hand of design knows what the left hand of construction is doing, and vice versa.