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Structural Tolerances

The Problem and the Approach

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Increased public and political interest in highway construction as a result of the Interstate Highway Program has created an atmosphere in which inspectors and engineers are becoming more reluctant to exercise "engineering judgment" in acceptance or rejection of work. Under such conditions it becomes more important to develop a "statistical basis" or "tolerance curve" as specification controls, recognizing that laboratory preceision cannot be economically obtained under jobsite conditions.

•THE PROBLEM of permissible construction tolerances has plagued mankind from prehistoric time when he first acquired the capability of adapting the materials of his environment to serve better his needs or his convenience. The controversy which could result between the maker and the purchaser of the first stone wheel can be well imagined. How much out-of-round would be permitted? How smooth must the rim be? How much off-center could the axle hole be placed? These questions had to be resolved by compromise on tolerances that would satisfy the needs of the purchaser and would be within the capabilities of the maker to produce. This might be called "engineering judgment" and some sort of refinement of this process has followed the construction industry from the stone ages to the present.

The magnitude of the Interstate Highway Program has focused attention on every aspect of the highway construction industry. The huge expansion of plant and personnel required since 1956 to accommodate this program has undoubtedly contributed to a condition which resulted in imperfections in construction that might not have occurred in a normal program. The public and political interest inherent in such a program has probably resulted in a tendency to magnify some of the imperfections out of proportion to their real significance in producing a satisfactory finished product.

The specifications under which most highway structures are built comprise single values, minimum or maximum as the case may be, for strengths, dimensional tolerances, and other controls that govern the acceptability of materials or workmanship. These have been accepted for many decades as values that cannot be quantitatively or qualitatively departed from.

The increased layman interest, which has arisen due to Congressional investigations and so-called exposés by news media, has caused some politicians, laymen, engineers and contractors to question whether an absolute line can or should be drawn between the acceptable and the unacceptable. A "tolerance curve" or a "statistical approach" has been suggested as a possible solution. If such an approach is used, research must be relied on to determine the limits governing unquestioned acceptance, qualified acceptance subject to correction or penalty, and absolute rejection.

Before the hot light of publicity was focused on every project, many responsible engineers were inclined to accept minor noncritical departures from specification on the basis that no willful departure from specifications had occurred and that the value and integrity of the end product had not been impaired. Now engineers and inspectors appear to be more unwilling to risk the exercise of any engineering judgment, due to the unpredictability of the findings of a possible inspection in depth.

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Senator Jennings Randolph, speaking before the A. G. C. meeting in 1963 in New York, urged that a research task force attack the problem of creating a statistical approach to determine values governing Federal approval. He declared that highway elements cannot be constructed to the exactitude obtainable under laboratory control and do not need such exactitude. He cited increased cost, without corresponding benefit, of the application of the rigid single-value specification system which may result in acceptance or rejection of work with very minor difference in functional capability. Many contractors and engineers subscribe to Senator Randolph's views. Probably most laymen find it a reasonable approach. Nearly all of the institutes in the principal fields of construction have recognized the problem and have programs under way which they hope will ameliorate the situation. An important effort is being made by the ARBA with the U. S. Bureau of Public Roads.

Inherent in the statistical approach is the necessity for establishment quantitatively and qualitatively of ranges of values instead of absolute single values in specifications. Such statistical values can only be developed by intelligent research. The code adopted by the American Welding Society for acceptance of welds is considered to be a possible pattern for other processes. The code defines all imperfections that occur in welds. Some imperfections are causes for absolute rejection of a weld and some imperfections are acceptable if the size or frequency does not exceed certain limits. The permissible sizes and the permissible aggregate of imperfections within specified lengths are defined. By this code it may be determined without question which welds are acceptable, which may be corrected or which must be rejected. Perhaps research may point the way to similar codes for other construction processes.

A step forward was taken when AASHO included in the draft copy of Guide Specifications Section 105.3, "Conformity with Plans and Specifications," the following clause: "Less than exact or complete conformity, especially with those values that are not critical with regard to expected performance of the completed work, may be tolerated in instances where obtaining exact or complete conformity would not be economical." The intent of this clause reaffirms the principle of exercise of engineering judgment. However, it contains no reassurance or protection for the inspector who fears that his judgment may be questioned. Only a statistically developed range of permissible tolerances can give such assurance.

The problem rests with us; it is costing contractors and owners money that must come only from the public treasury. Its solution will result in increased efficiency and economy in the construction field. It is hoped that this symposium may make some small contribution to its solution.

Progress Report on the Establishment Of Tolerances in Highway Construction Specifications

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Highway engineers and contractors are being criticized for deviations from specifications, even though in many instances there are sound engineering justifications for permitting the deviations. This problem underscores the need for tolerance on specifications. This is a progress report on the establishment of these tolerances.

•WHEN THE American Road Builders' Association held its 60th Annual Convention in San Francisco in March 1962, Louis W. Prentiss devoted a major part of his annual report to a discussion of administrative changes he felt would benefit the highway program. In regard to highway specifications, he proposed not only that there be wider acceptance of deviations from specifications where justified by engineering judgment, but that the allowable tolerances based on this engineering judgment be written into the specifications to insure that the exercise of sound engineering judgment would not be interpreted by non-engineers as a "failure".

The ARBA Committee of contractors, organized to implement this proposal, first met with a group of officials in the U. S. Bureau of Public Roads headed by Robert F. Baker, Director, and H. A. Radzikowski, Deputy Director for Development, Office of Research and Development. We found that our problem was one of major concern to this office of the Bureau. The officials were convinced that there was much merit in using what they termed a statistical approach in analyzing the data gathered in the acceptance tests performed on completed highway and bridge construction projects.

The statistical approach begins with the taking of samples at random. The test results are then plotted on a curve. Typically, most of the test results fall on or near a line representing the thickness or density which has been specified, and a small number of tests either fall short of or exceed the specification. Thus, the typical curve is bell-shaped.

Analyses of this kind point the way to precise, scientific answers to the question of what deviation from the specified norm can be tolerated within the limitations of sound engineering. When this question is answered for various materials and conditions of use, the specifications can be adapted accordingly.

Because the objectives of the Office of Research and Development paralleled those of our Committee, we were able to assure the Bureau officials of our full support at that first meeting.

An action program for the Committee was then drafted to support the Bureau's work effectively. This four-part program is as follows:

1. To recommend an order of priority for application of this concept to highway construction specifications;
2. To assist the Bureau in gaining acceptance of this concept by industry and state highway officials;

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3. To support and cooperate in research and development projects at the state level; and
4. To present the contractor's point of view on practical applications of the concept.

It may be well now to take a closer look at how this statistical concept can be applied in the construction of highways and bridges. In this country, almost 3.5 million miles of roads and streets and hundreds of thousands of highway bridges, practically all constructed by contract, have withstood the test of long years of good service to highway users, which is the acid test of quality.

This high degree of quality must be maintained in new highways and bridges. The achievement of this objective in recent years has placed a greater burden on the highway engineer-contractor team. The increased burden has been generated by the rapid expansion of the highway program, new concepts in highway design, and other factors, such as the non-engineering highway investigation.

Some aspects of the current program affect quality control in the construction of highway bridges. To expand the highway program, the rate of construction had to be greatly accelerated. This means that constantly more bridge construction than ever before is being initiated all over the nation. The total productive capacity of highway bridge contractors has had to be increased to meet the accelerated demand.

This has been done. At the bridge sites, new, more efficient machines are moving material and compacting it into place to form the approaches at a faster rate than ever before. Larger mixers have increased the number of yards of concrete produced and placed in highway structures each hour. Increased use of offsite prefabrication of steel and concrete structural members has speeded up onsite construction operations. New contractors have entered the field.

Access control is a concept that has meant more bridges per mile in the current highway program. Separate structures to carry opposing traffic are not being built because of the medians required under new design criteria. This means more bridge construction, not only because the lanes are wider but also because more miles of multilane highways are being built to meet the needs of present and future traffic. Major structural members today frequently incorporate a variety of types of steel to take advantage of the greater quality and economy possible with these new materials. In short, the bridge construction business has increased both in quantity and in complexity, and the task of quality control has increased proportionately.

At the same time, new questions have been raised as to the adequacy of standard quality control procedures, particularly by investigators with backgrounds in law or accounting rather than engineering. The lawyer or accountant, reading a specification for an eight-inch thickness of some material, wants every measurement of that material to be precisely eight inches. If he finds a measurement a fraction of an inch over, he is concerned that the state may have wasted money by purchasing more of the material than was absolutely necessary. If he finds a measurement a fraction of an inch under, he worries about quality. This type of investigator is usually unimpressed with the contention that reasonable variations are normally permitted by the supervising engineer whenever, in his judgment, no material extra cost and no notable loss of quality are involved. The investigator insists the specifications mean or should mean exactly what they say.

The ARBA Committee on Tolerance firmly believes the engineer should be free to apply his engineering judgment to accepting materials and contractor performance on highway and bridge construction projects. A major portion of the Committee's effort is directed in support of the free exercise of engineering judgment. The development of standard deviation curves and their application to highway specifications will help to shore up the authority of the engineer.

Of course, the statistical approach to quality control is not a new concept. Many industries have developed the tolerance ranges for their products through the use of statistical analyses. In fact, this approach was used in the development of the precise quality control procedures used successfully during the construction of the AASHO Road Test bridges and highway sections. We see no real problem, therefore, in establishing

the validity of this concept to improve quality control on highway and bridge construction jobs. The problem is to secure acceptance and use. The joint effort of the ARBA Committee and the U. S. Bureau of Public Roads is producing results in this direction.

The ARBA Committee, through ARBA affiliated state contractor organizations, has contacted member contractors, material suppliers, and state highway officials. The need for realistic specifications has been discussed. The use of the statistical approach to improve both quality and economy has been pointed out. The response has been excellent and cooperation was assured by most of those contacted.

These discussions produced information as to the specifications requirements where the statistical concept would be applied most expeditiously and the areas in which improvements were needed most. This information has been made available to the U. S. Bureau of Public Roads which also has been informing its field personnel and state highway departments of the advantages of the new approach to improved quality control and economy in highway and bridge construction.

A list of critical areas for study in the BPR research and development program has been made and is included as the Appendix. It should be read with the understanding that it is a tentative list, subject to future revision and expansion.

Each study item on the list is accompanied by a summation of the characteristics of the study item which are defined by highway specifications. For example, the specification characteristics of asphaltic base are density and thickness. As a further step, each of the specification characteristics is classified as major or minor, depending on the importance of meeting close tolerances. To use the same example, the density of asphaltic base is in the major class, meaning that only a relatively small degree of deviation from the specifications can be accepted. On the other hand, the thickness of asphaltic base is placed in the minor class because a relatively large deviation in thickness will have no appreciable effect on the safety, performance and durability of the highway.

The computations of acceptable tolerances also will take into consideration the variations inherent in highway and bridge materials, construction processes, tests and measurements. These variations must be established by record sampling of completed highway and bridge construction projects and from new data obtained from projects now under way. This data will be the basis for establishing the standard deviations of materials, performances, tests and measurements that are involved in controlling quality on highway and bridge construction projects. They will be used to develop standard deviation curves or charts for the major quality control phases and to compute acceptable tolerances. Such standard deviations were computed for various materials and performance results on the AASHO Road Test (1).

The use of standard deviations developed in this manner to compute acceptable tolerances can put new realism into highway and bridge construction specifications. They are realistic to the extent that they take into account all of the known variations in materials, processes, methods of sampling and testing procedures and to the extent that these variations are properly evaluated. Conformance to specifications based on this concept will give assurance to the engineer that quality goals will be met and to the contractor that rejections of acceptable materials and performance are kept to a minimum.

The ARBA Committee has informed contractors of the need to expedite the development of this approach to more workable highway specifications. Their response has been gratifying. Mounting numbers are expressing their willingness to support this essential activity. Highway officials have been informed of the willingness of the American Road Builders' Association and its contractor members to assist in expediting this program.

The U. S. Bureau of Public Roads has been very active in this area. During November and December 1963, a team of Bureau engineers was in the field continuously. They held special meetings with state highway officials and BPR field personnel in each of the nine regions. The objective was to encourage the states to submit proposals for developing standard deviation curves in areas given first priority for study. These meetings have generated enthusiasm and action. Already project proposals are being received in the Washington office. The Alabama State Highway Department wants to undertake a

project with its 1½ percent funds to develop standard deviations and acceptance tolerances in various areas, such as in the amount of degradation that may occur during the processing of a highway material. For example, after a subbase material has been accepted at a quarry, pit or producer's plant, it is transported to the project where it is spread and compacted into place. Thereafter, the subbase frequently is subjected to vehicle and equipment traffic which may change the physical characteristics of the materials. Rain and other climatic changes may introduce still other changes. As a result, the initial tests of the material may differ from those made after the subbase has been completed. This is a serious problem to materials producers as well as contractors.

The Bureau will review these state research proposals as they are received to reduce undesirable duplication. In addition, it has assigned qualified personnel to monitor progress on such projects and to disseminate useful information as results are obtained. Here again, the ARBA Committee will assist.

The Bureau has let several pertinent contracts to private engineering firms as a part of its research and development program. This was done to expedite the development of guidelines and criteria that would be useful in applying statistically based acceptance tolerances in highway and bridge construction specifications. The results of these studies will be helpful in directing the 1½ percent fund projects toward the production of complete, uniform and widely useful data. One major contract has now been completed.

Probably the most significant development in this field is the tolerance provision in the AASHO Guide Specifications adopted in 1963. Section 105.03 in the general provisions recognizes the problem and establishes a broad base for tolerances. The ARBA Tolerance Committee reviewed and endorsed this provision, but it will mean little unless the tolerances are provided in the specifications.

Both the Bureau and the ARBA Committee have given high priority to efforts to gain widespread acceptance of the statistical concept in the development of highway and bridge construction specifications. Considerable progress as outlined here has already been made. Other applications, particularly as to the specifications for highway bridges and other structures, will be brought out.

Unrealistic specifications for highway and bridge construction add to the cost without a commensurate increase in quality. The adoption of the statistical concept and the incorporation in specifications of sound tolerances developed by utilizing the statistical concept will enable alleviation of many problems.

REFERENCE

1. The AASHO Road Test, Report 2: Materials and Construction. Highway Research Board Spec. Rept. 61B, pp. 111-150, 1962.

Appendix

AREAS TO BE STUDIED FOR STATISTICAL QUALITY CONTROL AND TENTATIVE ASSIGNED CLASSIFICATIONS TO VARIOUS CHARACTERISTICS OF MATERIALS AND PROCESSES[a]

Item	Characteristics	Class[b]
	(a) Portland Cement Concrete Pavement	
Pavement slab	Thickness	Major
	Air content of surface	Major
Plastic concrete	Slump	Major
	Air content	Major
	Cement content	Major
	Cylinder strength	Major

Item	Characteristics	Class[b]
Coarse aggregate	Grading	Major
	Durability	Major
	Passing No. 200	Major
	Deleterious materials	Minor
	Los Angeles loss	Minor
Fine aggregates	Grading	Major
	Fineness modulus	Major
	Passing No. 200	Major
	Sand equivalent	Minor
Cement	Alkali content	Major
	Strength	Major
	Air content	Minor
	(b) Hot Mix Asphaltic Concrete	
Asphaltic pavement	Density	Major
	Temperature at compaction	Major
	Thickness	Minor
	Surface tolerance	Minor
	Roughness	Minor
Asphaltic base	Density	Major
	Thickness	Minor
Asphaltic mix	Gradation of aggregate	Major
	Dust ratio	Major
	Asphalt content	Major
	Mixing temperature	Major
	Stability and flow	Minor
Asphalt cement	Penetration or viscosity	Major
	Retained penetration of thin residue	Major
	Thin film test loss	Minor
Aggregate	Los Angeles loss	Major
	Gradation	Major
	Liquid limit and plastic index	Major
	Durability	Minor
	Deleterious material	Minor
	Flat and elongated particles	Minor
	(c) Base Course	
Soil aggregate	Stability	Major
	Plasticity	Major
	Thickness	Minor
	Gradation	Minor
	Density	Minor
	Line and grade	Minor
Stabilized base	Stability	Major
	Additive quantity	Major
	Thickness	Minor
	Plasticity	Minor
	Gradation	Minor

(d) Soils		
Subgrade	Density	Major
	Stability	Minor
	Moisture content	Major
Embankment	Density	Minor
	Moisture	Minor

[a] Prepared by the Task Force Group on Statistical Quality Control, Office of Research and Development, U. S. Bureau of Public Roads; these tables subject to additions and changes as the project develops.

[b] Major—a relatively small degree of deviation acceptable; Minor—a relatively larger degree of deviation acceptable.

Structural Steel Construction Tolerances

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•THE ARTICLE by Congressman Jim Wright and the comments by Senator Randolph to AGC support Mr. Scurr's view that the public interest in the highway program has resulted in a tendency to magnify some of the imperfections out of proportion to their real significance. Most of the irregularities which have been brought to light and highlighted in the "exposés" of the highway program appear not to involve questions of the adequacy of the established tolerances. For example, right-of-way acquisitions have no bearing on construction tolerances and yet irregularities in this area of activity seem to be the major subject of discussion in the news media. Many other irregularities involve situations where established tolerances cover the required quality and accuracy of the finished product but have been ignored. If these observations reflect the true situation, then changes in construction tolerances should be carefully considered so that they do not reduce tolerance limits unnecessarily or impose tolerance specifications to achieve accuracy of workmanship for accuracy's sake.

However, there has been very real evidence of an increase in the incidence of poor workmanship as the pace of the highway construction program was stepped up. As an institute vitally interested in highest quality workmanship in all fabricated steel work, the AISC finds reports of such evidence disturbing and is eager to take part in the activities of any task force to establish improved workmanship standards.

There are, no doubt, a number of reasons for establishing tolerances; however, the following are probably the most compelling ones as far as steel construction is concerned:

1. Accuracy required for structural integrity. Probably the best example of a tolerance to insure structural integrity is the straightness requirement for metal compression members. Generally, the straightness requirements for structural members are those published in ASTM A-6, which encompasses the dimensional tolerances for plain material as produced by the mills. The limits provide for material which is satisfactory for average work and within the capabilities of the mills to produce on a mass production basis without resort to special operations that increase costs. For compression members, however, the straightness tolerances of ASTM A-6 are usually tightened somewhat in most specifications due to the consequences of a compression member failure and the increase in tendency to buckle as eccentricity is increased. For the most part, the tolerances for welded members are the same as those for rolled members produced under ASTM A-6, even though rolling mill practice has only limited direct bearing on welded built-up members. One particular tolerance requirement to insure structural integrity involves the tilt or out-of-square limits for flanges. It can be readily seen that a bad match on the tilt of the abutting flanges would make welding a proper joint difficult.

2. Accuracy required for dimensional function. Structural adequacy would not be affected by inaccuracies in the fabrication of roadway expansion devices, but if the camber of such a device does not match the crown of the roadway, the paving trades cannot properly execute their work.

3. Accuracy required for appearance. In this category are the web plates of a plate girder which were buckled out of plane between stiffeners due to welding distortion. Such a member, within reason, would be as strong structurally and as functional dimensionally as a similar girder without such inaccuracies; however, strictly for appearance it might be desirable to limit this out-of-flat condition.

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One aspect is common to all of the above examples. All are dependent on the requirements of the user or the functional purpose of the piece or structure as a whole. The ability of the producer is not relevant. This is as it should be. Modern machines and techniques are capable of producing work of sufficient accuracy to satisfy the realistic requirements of structural integrity, dimensional function, and appearance.

To guide the discussion in this seminar, comments were requested relative to four specific topics:

1. The adequacy of existing specification tolerances. As previously pointed out, much of the deficient workmanship which has been the subject of discussion has resulted from irresponsibility on the part of those actually executing the work and those charged with checking and inspecting the results. No amount of tightening the limits of existing provisions or increasing the number of provisions to achieve greater refinement of the rules will improve the quality of the work if failure to adhere to the rules continues. Evidence that the tolerance provisions are too loose would be found where all provisions are met and the resulting piece or structure is not functionally satisfactory. Also, an indication that the existing tolerances are inadequate might be found where unsatisfactory results are produced because there are no rules to cover the particular situation. Since cases of this nature apparently do not exist, it can only be assumed that existing tolerance specifications provide adequate rules if they are observed.

2. The desirability of modifying existing tolerance as a result of current developments in materials and construction methods. The thought here is to make tolerance limits more restrictive as improvements in machines and technique make greater accuracy more easily attainable. Objectively, however, tolerances should proceed from the requirements of the end product. To establish closer limits on the required accuracy of workmanship than is required for the proper performance of the individual piece or structure would be to specify refinement and a high degree of accuracy for accuracy's sake. And cost of the work increases by a geometric function as the required accuracy approaches the zero tolerance area. Thus, even though modern equipment may be readily capable of producing work to a greater degree of perfection, the realization of the increased accuracy in the end product will not be without cost if the fabricator is required to guarantee such accuracy by the terms of the contract or specification. For example, in high-strength bolted joints, if a tolerance on the misalignment of the plies of material that make up a joint is limited to a 1/32-in. offset at the edge of a hole as compared with 1/16-in. permitted offset, there would be no measurable difference in the strength of the joint. Thus, with a 100 percent increase in the permitted inaccuracy, or with a 50 percent decrease in the tolerance limit, there would be no difference in the functional quality or appearance. Reducing the tolerance limits simply because machines and techniques may make such accuracy attainable would serve no useful purpose and would most certainly result in increased cost.

It may be felt that such an example is absurd, but actual examples may be cited which are even more absurd. In one instance, a fabricator was required to purchase specially ground undersized reamers because an inspector found by using a micrometer that a standard reamer produced holes slightly larger than its nominal size. He was interpreting 1/16 in. larger than the nominal size of the bolt as meaning not more than 0.0625 in. Tests at Illinois University have demonstrated that holes 1/8 in. larger than the nominal size of the bolt result in no loss of strength. Therefore, in this case, refinement of the accuracy of alignment of holes beyond present limits would avail nothing.

There may be areas where the improvements in materials and construction procedures should be taken into account, for example, where the requirement for accuracy in the finished work or the improved usefulness of a more accurate piece or structure would be possible now, but in the past was economically unattainable. In such a case, a joint effort on the part of the owner-designer and the producer to work out an economical balance between the desired and the attainable would be beneficial.

3. The desirability of development of so-called tolerance curves. The statistical approach to the measurement of the acceptability of a large number of identical mass-produced items is well recognized in modern practice. It is the only feasible method for checking such things as fasteners, and a good example of its use may be found in the new Recommended Practice for Acceptable Quality Level for Standard Commercial Bolts, Screws, Nuts, Rivets and Similar Fasteners, approved by the Industrial Fasteners Institute in July 1963. Tables of major and minor defects for various fasteners are provided, as well as a schedule of size of sample required and the accept and reject percentages for various quality levels. The system is workable for mass-produced items of this type that are purchased in large quantities, but unworkable for structural elements other than fasteners and similar items.

As the author understands "statistical approach," a large number of similar items are required. It is impossible to apply statistics to one or two similar items. Either the piece has dimensional characteristics and properties which make it suitable or it does not. It cannot be rejected and replaced by another similar item from a bin. From this point of view, how may the statistical approach be applied to structural components?

On the other hand, a different sort of "tolerance" curve may have been implied. Reference has been made to different levels of acceptability in which unqualified acceptance would be accorded work that is within specified limits. Work containing defects falling outside the limits for unqualified acceptance could be accepted if the defects are corrected. This seems to have been the situation for many years in fabricated steel work. For example, there is no reason why material with unfair holes should not have the holes welded up, the surface ground smooth, and new holes properly drilled. After such corrective work, the piece would be as good as a piece in which holes were properly located in the first place. It is not apparent how a tolerance curve would be applicable in this case. Either corrections could be made by means which do not harm the material and the piece made to conform to the primary required accuracy limits of workmanship standards or it should be rejected.

The final item on which comments were requested was relative to the type of research necessary to establish tolerance values. Over the years, many thousands of steel structures have been built. Each one of these might be thought of as a research structure as far as tolerance limits are concerned. Where such past work has revealed the need for the establishment of tolerances, that has been done; where no such need has been demonstrated, no specified tolerance provisions have been put into effect. This is as it should continue to be in the future.

Before concluding, it would be well to point up one area wherein some improvement may be possible. The problem occurs because of a difference of opinion between shop inspectors and field inspectors. On occasion, reports are received where work has been checked and approved by the owner's agent in the shop only to be rejected by the field inspector. Obviously, where dimensional errors are involved or where there is a real deficiency involving the adequacy of the piece, the fabricator should make corrections without question. However, where workmanship tolerances are involved which are purely a matter of opinion between two inspectors, the added cost of making corrections in the field over the cost of reworking in the shop should be the owner's responsibility. For example, there are differing opinions as to what constitutes adequate grinding of butt-welded splices in tension flanges. Another example involving quality requirements is the interpretation of radiographs. It seems strange that a joint may be approved on the basis of a radiograph and shipped, only to be rejected later on the basis of another interpretation of the same picture. No doubt, it will be impossible to eliminate the human factor, and most individuals connected with construction would not favor working under a system of tolerance limits so complete that engineering judgment was eliminated.

In summary, based on a sampling of the opinions of knowledgeable fabricators from all parts of the country, the tolerances for fabricated structural steel work which are presently in force are considered to be adequate. Any new tolerance provisions should objectively be based on the requirements for structural integrity, dimensional function, and appearance. Tolerances should not be made more restrictive simply because new

machines and techniques make refinement possible. Where it is appropriate, a statistical approach to tolerances is much to be desired, but in the case of fabricated structural steel, it does not seem to provide a useful technique.

Construction Tolerances for Concrete in Highway Structures

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Construction tolerances for concrete now generally specified or recommended in various design standards are discussed. The need for new tolerance criteria is stated, and a basic approach to tolerancing as a function of design is proposed, taking into account service requirements, structural integrity, and appearance of concrete construction.

•TOLERANCES IN CONCRETE work involve both qualitative and quantitative factors. Although concrete is a "manufactured" material, the application of scientific tolerancing in concrete construction has not been considered to any extent in engineering and design procedures. Unfortunately, the lack of tolerance information in contract documents has led to misunderstanding and controversy among architects, engineers, inspectors and contractors regarding acceptance of concrete construction. Specifications such as "Surfaces cast to true planes" or "Contractor to verify all dimensions in the field" leave much to the imagination of the resident engineer, inspector and contractor.

In the past, most concrete structures have been cast in place, usually designed with conservative working stresses and adequate margins of safety. The dimensions have been made to fit by a process of adjustment to previously built parts. The recent trend in the direction of ultimate strength design with higher working stresses and lighter concrete sections reinforced with high-strength steels will demand greater precision of concrete manufacturing and workmanship. Qualitative and quantitative tolerancing will become a part of the engineering and design procedure.

NEED FOR RECOGNITION OF TOLERANCES

In concrete construction tolerances are necessary in relation to three important aspects: (a) integrity and safety of the structure, (b) aesthetics or appearance of the finished work, and (c) economics, involving cost to owner, designer, or contractor.

Integrity and Safety of Structure

Quality of concrete is influenced by manufacturing tolerance measured by a coefficient of variation. The American Concrete Institute (ACI) Standard 214-57, Recommended Practice for Evaluation of Compressive Strength of Field Concrete, discusses the relationship between concrete mix design strength and specified strength as a function of the variation in cylinder strength obtained on the job. This relationship is illustrated in Figure 1. By maintaining a tight tolerance in the manufacture of concrete, the ratio of required strength of concrete mix to specified strength can be kept to a minimum. Thus, the specified concrete strength should recognize a tolerance in cylinder test strengths (1).

Quantitative tolerances related to integrity and safety of structure are dimensional or geometric. The concrete section, effective depth of reinforcement and cover over reinforcing steel affect integrity and strength. In precast concrete construction, dimensional accuracy may affect the stresses at connections between members.

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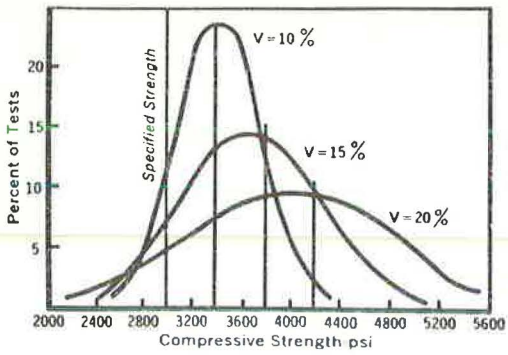

Figure 1. Relationship between coefficient of variation and required average cylinder strength to satisfy specified strength of concrete.

Aesthetics—Appearance of Finished Work

The satisfactory composition of a concrete structure usually depends on conformity with design dimensions within certain tolerances. The designer visualizes the columns or piers plumb, the girders level or set to an established camber or grade. He expects the final structure to correspond to the appearance shown on his drawings. Since no concrete structure is ever built exactly true to every plan dimension, tolerances should be specified, informing the contractor within what limits he must adhere to the theoretical dimensions. Allowances for shrinkage and creep of concrete should be anticipated in setting the tolerances. If no tolerances are specified, who is to judge how much variation from plan dimensions constitutes satisfactory compliance with the contract?

The finish of concrete surfaces exposed to view should be specified within reasonable tolerances. Uniformity of color and texture of surface should be defined, either by illustrations or standard samples for the benefit of contractors and inspectors, showing a range of acceptability for a given project.

Economic Aspects

John R. Nichols stated (2):

> Tolerances must be related on the one hand to their reasonableness, to the cost of building within them; and on the other hand to the need for, and the value of, close adherence to the indicated line and grade. In judging any proposed tolerance, therefore, one must inquire first, is it necessary and is it sufficient to build within this tolerance in order that the structure may have suitable appearance, may satisfy the purpose for which it is erected, and may be structurally safe; and second, can such accuracy be obtained reasonably, that is, without unjustified cost?

In 1940, Nichols was thinking of cast-in-place concrete construction. Today, concrete construction is moving toward prefabrication of structural members and becoming an industrialized process in which mass production of factory-manufactured structural elements will prevail. Already highway structures are being assembled from precast and prestressed concrete parts which are factory produced and delivered many miles to the construction site. The economy of prefabricated concrete structures is becoming more obvious as savings in labor and material are achieved through better designs and the exploitation of very high-strength concrete (6,000 to 10,000 psi) and prestressing steel (250,000 to 300,000 psi). As Abdun-Nur pointed out (1), average field-produced concrete may be assumed to have a compression strength coefficient of variation between 20 and 25 percent. Factory-produced concrete, scientifically controlled, may have a coefficient of variation of 10 percent, with important economic implications. Thus, the designing engineer should be concerned with qualitative tolerances related to concrete strength.

With prefabricated concrete construction, dimensional tolerancing takes on new importance. As in other manufacturing industries, such as the automotive and aircraft, mass production and assembly of parts involve tolerances for dimension, form, and position. Over the past 40 or 50 years, the automotive and machine tool industries have evolved an advanced concept of tolerancing. Today, national and international

CHARACTERISTIC	PRESENT	NEW	ISO
STRAIGHTNESS	⌒	—	—
FLATNESS	⌒	—	▱
ANGULARITY	∠	∠	∠
SQUARENESS	⊥	⊥	⊥
PARALLELISM	∥	∥	//
CONCENTRICITY	◎	◎	◎
TRUE POSITION	⊕	⊕	⊕
ROUNDNESS	○	○	○
SYMMETRY	≡	≡	≡
ACCURACY OF LINE OR PROFILE		⌓	⌒
ACCURACY OF SURFACE		⌓	⌓
RUN OUT		↗	↗
CYLINDRICITY		⌭	⌭
DATUM	-A-	-A-	▲
MMC	Ⓜ	Ⓜ	Ⓜ
RFS	Ⓢ	Ⓢ	

Figure 2. Symbols for geometric and positional tolerancing.

societies are working on standards for tolerancing and means of communicating design tolerances on drawings and specifications. Belitsos (3) traced the evolution of the technology of graphics from its very simple beginnings to a highly sophisticated language of communication between engineering, manufacturing and inspection. Figure 2, taken from this article, shows tolerance symbols for geometric and positional tolerancing.

CURRENT STATUS OF TOLERANCING FOR CONCRETE CONSTRUCTION

Tolerancing in concrete construction today is comparable to the situation in the automobile industry 60 years ago. Each part was made to fit to its neighbor by selective assembly. An overrun in dimension of one section was deducted from the dimension of an adjacent section so that the overall total would add up to the desired sum.

In current practice of highway design, the only widely used tolerance for concrete structures relates to the surface of the roadway, namely, a maximum deviation from the design surface of $\pm\frac{1}{8}$ in./10 ft of distance.

The American Concrete Institute Standard 347-63, Recommended Practice for Concrete Formwork, contains suggested tolerances for concrete bridge structures. These tolerances give plus or minus limits of permitted departure or variation from the design dimensions, summarized as follows:

1. Departure from established alignment, 1 in.
2. Departure from established grades, 1 in.
3. Variation from plumb or specified batter in the lines and surfaces of columns, piers, walls, and arrises—exposed, in 10 ft, $\frac{1}{2}$ in.; backfilled, in 10 ft, 1 in.
4. Variation from level or grades indicated on drawings in slabs, beams, horizontal grooves, and railing offsets--exposed, in 10 ft, $\frac{1}{2}$ in.; backfilled, in 10 ft, 1 in.
5. Variation in cross-sectional dimensions of columns, piers, slabs, walls, beams, and similar parts, $-\frac{1}{4}$ in., $+\frac{1}{2}$ in.
6. Variation in thickness of bridge slabs, $-\frac{1}{8}$ in., $+\frac{1}{4}$ in.
7. Footings—variation in dimensions in plan, $-\frac{1}{2}$ in., +2 in.; misplacement or eccentricity, 2 percent of footing width in direction of misplacement but not more than 2 in.; reduction in thickness, -5 percent of specified thickness.

The contractor is expected to set and maintain concrete forms to insure completed work within the tolerance limits.

Suggested tolerances for precast concrete construction are also included in ACI 347-63, as follows:

1. Overall dimensions of members per 10 ft of length, $\pm\frac{1}{16}$ in.
2. Cross-sectional dimensions of sections less than 3 in., $\pm\frac{1}{16}$ in.; of sections over 3 in. and less than 18 in., $\pm\frac{1}{8}$ in.
3. Deviations from straight line in long sections, not more than $\frac{1}{8}$ in./10 ft.
4. Deviation from specified camber per 10 ft of span, $\pm\frac{1}{16}$ in.; maximum differential between adjacent units in erected position, $\frac{1}{4}$ in.

These tolerances are considered too restrictive by most precast concrete manufacturers, and counterproposals with liberalized tolerances have been suggested, such as the Michigan Precasters Recommendation:

1. Cross-sectional dimensions—less than 6 in., $\pm\frac{1}{8}$ in.; 6 to 18 in., $\pm\frac{3}{16}$ in.; 18 to 36 in., $\pm\frac{1}{4}$ in.; over 36 in., $\pm\frac{3}{8}$ in.
2. Length, $\pm\frac{1}{8}$ in./10 ft; maximum deviation, $\pm\frac{3}{4}$ in.
3. Deviation from line (sweep), $\frac{1}{8}$ in./10 ft.
4. Deviation from specified camber (as installed), $\pm\frac{1}{8}$ in./10 ft.
5. Differential camber in adjacent units (as installed), one-half total allowance.
6. Vertical deviation in squareness of ends[1]—less than 12 in., $\frac{1}{32}$ in./in.; over 12 in., $\frac{3}{16} + \frac{1}{64}$ in./in.; maximum deviation, $\frac{3}{4}$ in.
7. Horizontal deviation in squareness of ends[1]—less than 12 in., $\frac{1}{64}$ in./in.; over 12 in., $\frac{3}{32} + \frac{1}{128}$ in./in.; maximum deviation, $\frac{3}{4}$ in.

These tolerances are considered standard in the Michigan area for the various precast concrete items including columns, beams, single and double tees, hollow core and solid slabs. Allowances should be made in the design to accommodate these standards wherever possible. If closer tolerances are necessary, they should be clearly noted on the drawings and in the specifications.

Tolerances for surface finishes have been published by the U. S. Bureau of Reclamation in "Concrete Manual", 1963 Edition. Five classes of finishes for concrete surfaces cast against forms are designated as F1 through F5. Four classes of finishes for unformed surfaces are designated as U1 through U4. Surface irregularities permitted for these finishes are termed either "abrupt" or "gradual." Offsets and fins caused by displaced or misplaced form sheathing, lining or form sections, by loose knots in forms, or by otherwise defective form lumber are considered as abrupt irregularities. All others, classed as gradual irregularities, are measured with a template consisting of a straightedge for plane surfaces or its equivalent for curved surfaces.

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[1] This not to be in addition to overall length tolerance.

TABLE 1
MAXIMUM ALLOWANCES OF IRREGULARITIES IN CONCRETE SURFACES

Type of Irregularities	Formed Surfaces[a]					Unformed Surfaces[b]			
	F1	F2	F3	F4	F5	U1	U2	U3	U4
Depressions	1	-	-	-	-	-	-	-	-
Gradual	-	1/2	1/4	1/4	1/4	-	-	-	-
Abrupt	-	1/4	1/8	1/4[c] 1/8[d]	1/4	-	-	-	-
All surfaces	-	-	-	-	-	3/8	1/4	1/4	-
Canal surfaces, bottom slabs	-	-	-	-	-	-	-	-	1/4
Canal surfaces, side slopes	-	-	-	-	-	-	-	-	1/2

[a] Measured from 5-ft template.
[b] Measured from 10-ft template.
[c] Of irregularity or offset extending parallel to flow.
[d] Of irregularity or offset not parallel to flow.

The various classes of finishes and the categories of construction where applicable are described. The allowable irregularities in concrete surfaces for the various classes of finishes are given in Table 1.

Tolerances for the fabrication and placing of reinforcing steel, although very important, have not received much notice in technical publications. Nichols (2) did propose the following allowable variation from plan dimension in the fabrication and placing of reinforcing steel:

1. Variation from dimension in the fabrication of stirrups, column ties and spirals, 1/4 in.; of other bars, 1/2 in.
2. Placement of reinforcement affecting protective covering or effective depth in bending, in slabs and members not over 1 ft in transverse dimension (in the direction of the tolerance), 1/4 in.; in other members, 1/2 in.
3. Spacing of bars indicated to be evenly spaced in a group—variation from even spacing, 2 in.; variation in average spacing affecting the number of bars in the group, 5 percent; minimum clearance between parallel bars, 1/4 in.

The ACI Detailing Manual for Reinforced Concrete includes information on tolerances for fabrication of reinforcing steel, shown in Figure 3. These tolerances reflect standard practice in the cutting and bending of steel by reinforcing bar fabricators.

Obviously, available published tolerance data on reinforced concrete construction reflect consideration for safety, appearance and economy of concrete construction. Unfortunately these data are not generally incorporated into construction contract documents. Provision for enforcement of tolerances in construction creates problems for resident engineers and inspectors and this area needs more attention.

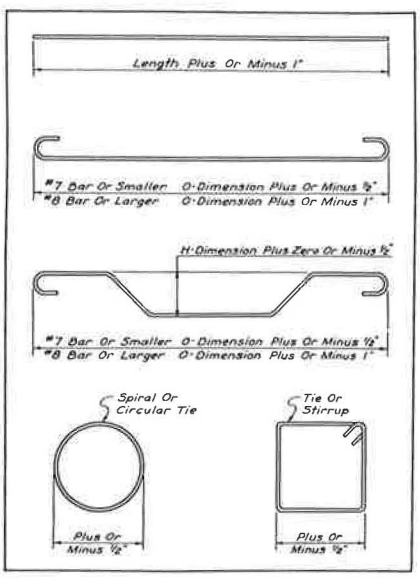

Figure 3. Tolerances for cutting and bending reinforcing steel, from ACI detailing manual.

A review of tolerances for reinforced concrete construction gathered from published sources indicates that values seem reasonable for average practice. However, no basic formula has been proposed for tolerancing in function of total dimension of members. Nothing reflects percentage variation of lever arm ratios in reinforcing steel or eccentricity of forces in compression members. Thin-wall hollow cylinder piles are not distinguished from large diameter cast-in-place reinforced concrete columns. Tolerance figures of 1/8, 1/4, and 1 in. seem to be popular values put into tables.

CONCLUSIONS

A need exists for a logical system of tolerancing concrete structures from the standpoint of safety, aesthetics and economics of concrete structures. Lack of adequate concrete tolerance communication in contract documents has led to misunderstandings and disputes between engineers and contractors, often resulting in litigation.

Construction trends are shifting to prefabrication, with mass-produced components requiring accurate fitting into final assembly. Tolerancing must become an engineering and design procedure. Much can be learned from those in other fields of engineering who have developed tolerancing to a highly logical and scientific procedure in design. Concrete engineering and construction needs a language of tolerancing for communication between the designers and the builders.

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Construction Tolerances—Prestressed Concrete

R. J. LYMAN, Prestressed Concrete Institute

•THE MANUAL for Inspection of Prestressed Concrete was prepared by a joint committee composed of members of the AASHO Committee on Bridges and Structures and representatives of the Prestressed Concrete Institute. Its purpose is to provide uniform inspection procedures for the manufacture of bridge members. Some of the state highway departments have also developed their own manuals which, when coupled with special specification provisions and appropriate project drawings, comprise the contract documents for specific projects (Fig. 1).

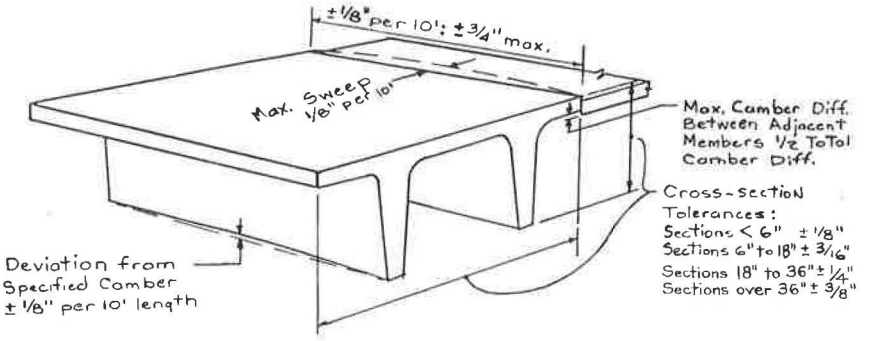

Figure 1. Dimensional tolerances.

Bill Dean of Florida, Chairman of the Joint AASHO-PCI Committee which prepared the Manual, said,

> Regarding the tolerances as published; first, they were not considered by the committee to be sacred and next, they must be applied with judgment and understanding. . . . During preparation of the manual the subject of inclusion of a table of dimensional tolerances was proposed several times. During our two-day meeting, in which the text of the manual was finalized, we had for reference tolerance tables prepared by several states and by some producers. Each tolerance dimension as listed, was brought up, considered and agreed to by the full committee.
>
> To my best knowledge, this table of tolerances has been given a wider distribution than any published heretofore. It is not surprising that some objections have developed and some suggestions for improvement have been made . . . .
>
> To sum up: The published tolerances are not to be considered as forever binding. This represented the best judgment of the committee members at the time the manual was published; improvements and modifications will surely be developed; any set of dimensional tolerances should be applied with judgment and some understanding of member functions.

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The general feeling among interested engineers appears to be that tolerances should be a guide to promote minimum requirements throughout the industry as well as an indication of a reasonable standard of performance and should not be a hindrance in obtaining more exacting workmanship. They should not be regarded as rigid and sacred. Specific job conditions may require separate tolerances, either closer or more liberal.

Specific portions of the table of tolerances contained in the AASHO-PCI Manual have been commented on by various bridge engineers and prestressers. Joseph Kirby, Bridge Engineer, North Dakota State Highway Department, states:

> Plus or minus camber tolerances could allow too great a difference between adjacent beams while a gradual change from a plus tolerance on one side of a structure to a minus tolerance on the other side could be satisfactory. Tolerances should therefore be specified in relation to the group of beams and not individually (unless an extremely small tolerance is specified).

On the same subject, H. B. Schultz, Engineer of Bridges, Wisconsin State Highway Commission, states:

> I hope that generally manufacturing procedures will improve to the extent that the tolerance for camber may be reduced. This should be possible as more producers adopt external vibration, thus making it possible to compact concrete that is uniformly of a very low slump.

Comments were received from C. A. Pestotnik, Bridge Engineer, Iowa State Highway Commission, as follows:

> We have had a problem with prestressed beams at bearing seats. Although the bearing area at each end of a beam may be a flat, true plane and normal to the web, we have found beams with a slight twist that results in edge bearing at one or both ends of the beam when placed on the bridge seats.

He further recommends a change in the tolerance table: "Bearing Plate or Bearing Area Deviation from plane: We prefer $\pm 1/32''$ rather than $\pm 1/16''$." On the camber problem, Mr. Pestotnik says,

> Recently, we have conducted a limited investigation to measure the initial centerline camber of thirty-four identical 100′ pretensioned prestressed concrete beams. In order to minimize the effect of creep, the cambers were measured as soon as the prestress was released. The camber readings thus obtained were consistent, and in close agreement with the calculated cambers. These beams are now being erected and their cambers will again be checked in the spring of next year (1964) prior to the placement of concrete floor slab. From our past experience, the "final" cambers were far from consistent even for identical beams. We wholeheartedly support the idea of additional research concerning cambers in order to enable the designer to predict the camber more accurately and to establish more appropriate tolerance values.

Several prestressers in Wisconsin have suggested that the horizontal alignment tolerance for box beams and slab sections should be liberalized somewhat for members more than 40 ft long. It was suggested that an increase from $3/8$ in. to $1/2$ in. for lengths from 40 to 60 ft be considered and from $1/2$ in. to $3/4$ in. for lengths greater than 60 ft. From the same group comes the suggestion that the "head out of square" tolerances for prestressed piling be increased from $1/16$ in. in 12 in. to $1/8$ in. in 12 in.

Carl E. Thunman, Jr., Assistant Engineer of Bridge and Traffic Structures, Illinois Division of Highways, comments as follows:

> For example, some individuals wanted very close camber controls on prestressed I-beams as they felt that high cambers and variable cambers resulted in the necessity of either increasing the thickness of the cast-in-place slab or required that the top of the beam be embedded excessively into the slabs. Others were willing to accept a more liberal camber control on I-beams due to the fact that they detailed their structures, allowing for camber; and maintained a constant depth cast-in-place slab by providing a variable depth fillet between the top of the beam and the bottom of the slab. This is just one example; however, I think it serves to point out that the details of each particular application of a precast prestressed member control to some extent acceptable tolerances . . . .
>
> In determining tolerances we have tried to select tolerance limits which are practical to attain with conventional methods and equipment used by the prestressed concrete industry and at the same time recognize the effect of such tolerances on our use of the products. Following are some of the items which were considered in determining tolerances.
>
> The effect of the tolerance limits in cross-sectional dimensions was evaluated to determine how much variance would affect the structural properties of the member. The effect of the accuracy of the prestressing force was investigated to determine the behavior of the beam at extreme ranges of tolerance. Incidentally, with specification writers now considering allowable tension in the precompressed tensile zone of prestressed concrete bridge members, I feel that the question of accuracy of the prestressing force becomes more significant than ever before. While admittedly the magnitude of the prestressing force has little or no effect on the ultimate capacity of the prestressed member, it does have a pronounced effect on the magnitude of the cracking load, and, consequently, on the behavior of the member since the member does lose stiffness at and beyond the cracking load. With the trend in specifications going toward allowable tensions under full design loads, I feel that the accuracy of the prestressing force assumes more significance than previously.
>
> The effect of dimensional tolerances on the problems arising in incorporating a precast element into the final structure in the field was given consideration. For example, the effect of tolerance in overall length of the beam on positioning the beam on the substructure unit and the effects of allowable tolerance in the width of the beam on the overall lay-up width of adjacent box beams were considered.
>
> Such things as the effect of allowable tolerance on the final function of the structure and the aesthetic effect were also taken into consideration.

Mr. Kirby of North Dakota says about post-tensioned beams:

> If camber is post-tensioned beams is adjusted during construction by varying the prestress force, the limits of this variation from the planned amount shall be ± 5%. Uniform camber in beams is dependent upon a uniform concrete mix and accurate placing and tensioning of prestress steel. Varying the prestress force within limits will offset these inaccuracies making beams more closely resembling the design requirements.

From the inspection standpoint there is another approach which has been discussed in an exploratory manner and may have some merit or at least bear further investigation and study. A possibility exists of establishing primary ranges of the tolerance which when specifically met would provide unqualified acceptance of work along with establishing secondary ranges for qualified acceptance subject to correction by the con-

tractor or penalty to the contractor for noncritical departures from specified tolerances. Adequate inspection of the fabrication and casting procedures in a prestressers plant facility will normally provide the basis for a determination of structural soundness of any prestressed concrete beam produced, whether or not the construction dimensional tolerances prescribed are complied with. However, the average inspector is occasionally faced with the situation wherein a particular beam has been found to exceed the allowable dimensional tolerance in noncritical physical characteristics, but in all respects is structurally sound. Of course, this is the situation that requires good judgment and understanding of the member function. This situation could be easily handled if a secondary range of allowable tolerances was specified which would provide the possibility of correction or the acceptance of a penalty by the contractor for a noncritical departure from the specified tolerances.

A corollary to the establishment of a secondary range of allowable tolerances has been used in recent months by a consulting structural engineer of Albuquerque, New Mexico, Fred J. Fricke:

> When an approved Laboratory 28-day Test and supplementary core boring of concrete of a certain pour fails to meet the strength of concrete required, and subsequent investigation by the engineer indicates that such low value concrete can be used in the structure a penalty of $10. per yard of such concrete poured will be assessed against the contractor; the contractor to have the option of paying the penalty or replacing the low value concrete.

Discussion with this engineer has revealed that the clause is bringing desired results and he intends to use it until a better solution appears. The citing of this example is not intended to imply recommendation of a similar approach but merely to show that action is being initiated by some engineers to try to solve the problem.

The premise of establishing primary and secondary ranges of tolerance in connection with prestressed concrete needs further study, but it does offer possibilities that can be explored.

In summary, based on contact with many engineers who have used the Manual for Inspection of Prestressed Concrete since its publication, it is evident that it has become the standard for the industry, particularly with regard to the tolerance limits established. To date PCI has published two manuals dealing with inspection and tolerances, and it is our aim to continue to review and revise this latest manual to improve the standard. It appears that in some areas which I have mentioned (bearing areas of beams, horizontal alignment of long beams, accuracy allowances in measuring prestressing force, and end squareness of prestressed piling), further consideration, review, and analysis may be needed. To this end the background information and data collected and developed in the preparation of this paper will be furnished to the Joint AASHO-PCI Committee for evaluation. It has become apparent that the general area of camber, and particularly differential camber, needs considerable additional detailed study to arrive at more representative and realistic construction tolerances. The Technical Activities Committee of the Prestressed Concrete Institute already has this as an agenda item and will have several committees working in this area of responsibility. It is hoped that the results of these studies will soon be available for the highway bridge program.

Dimensional Tolerances and Quality Control in Welded Steel Construction

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Recently the American Welding Society issued two regulations for welded construction—one for buildings and the other for bridges. A brief discussion is given of the pertinent clauses devised to provide an acceptable quality of workmanship and to specify the limits of dimensional deviation obtained in welded fabrication.

•FABRICATION tolerances in welded steel construction may be considered under two general headings: (a) tolerances pertaining to the dimensional makeup or configuration of a member built of welded parts, and (b) tolerances concerned with the quality or acceptability of the welds alone.

Certain configurational deviations are inherent in welded fabrication. Because of the generated intense heat of fusion and the subsequent cooling of the weld melt, some distortions in the assembly would occur, regardless of the care exercised. The extent of these distortions will vary, according to the geometry and retention of the assembly, the size and thicknesses of the components, and the type and sequence of welding. Allowable limits for such deviations are covered in two documents recently issued by the American Welding Society: Code for Welding in Building Construction, AWS D1.0-63; and Specifications for Welded Highway and Railway Bridges, AWS D2.0-63. The prescribed tolerances cover: (a) deviations from straightness for columns; (b) camber, sweep, warpage and web buckles for beam and girders; (c) deviations from flatness for seats and faying surfaces; and (d) variations in depths of built-up members.

These tolerances have created no serious problems, either in design or fabrication, to require reexamination or changes at this time. However, with the benefit of advanced welding technology and improved equipment and procedures, it may be possible in the future to fabricate welded assemblies conforming to still smaller dimensional tolerances than presently required or obtainable.

In contrast, the problem of acceptability tolerances for the weld itself is a thorny one. In reality, here we have two questions to answer. First, we must define an acceptable weld. Then, based on that definition, we must devise ways and means to assure that such a weld is obtained.

The AWS Building Code, under heading of Quality of Welds, defines an acceptable weld as follows:

> (a) The weld shall be sound throughout. There shall be no crack in any weld or weld pass. The weld may be considered sound if it contains only slight porosity[1] or fusion defects[2] which are well dispersed.

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[1] Porosity signifies gas pockets and any similar generally globular type voids.
[2] Fusion defect signifies slag inclusions, incomplete fusion, inadequate penetration and similar generally elongated defects in weld fusion.

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(b) Undercut shall not be more than 0.01 in. deep when its direction is transverse to the primary stress in the part that is undercut. Undercut shall not be more than 1/32 in. deep when its direction is parallel to the primary stress in the part that is undercut.

(c) Welds shall be free from overlap.

(d) All craters shall be filled to the full cross-section of the welds.

Under the same heading, the Bridge Specification gives the following:

(a) There shall be thorough fusion between weld metal and base metal and between successive passes in the weld. All craters shall be filled to the full cross-section of the weld.

(b) Welds shall have no cracks and, regardless of the method of inspection, shall have no other defects exceeding the following limits in size or frequency of occurrence:

(1) The greatest dimension of any porosity or fusion defect that is 1/16 in. or larger in greatest dimension shall not exceed the size Dimension of Defect, B, indicated in Fig. 409 [Fig. 1 herein] for the joint or weld throat thickness involved. The

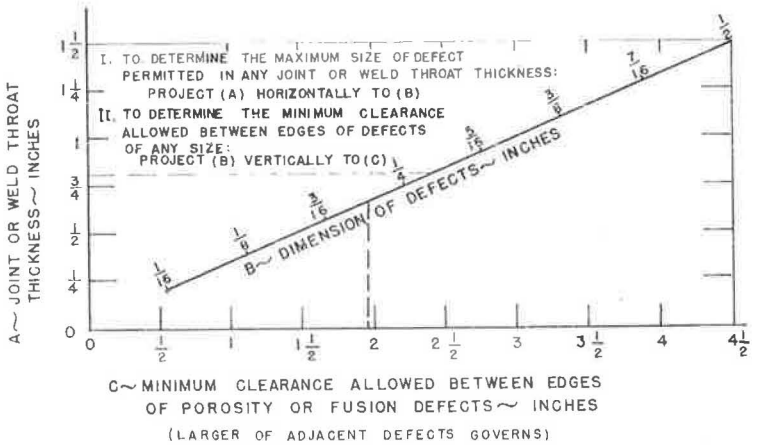

Figure 1. Weld quality requirements (limitations of porosity and fusion defects).

distance from any porosity or inclusion type defect to another such defect, to an edge or to the toe of a flange-to-web fillet weld shall not be less than the Minimum Clearance Allowed, C, indicated by Fig. 409 for the size of defect under examination. The limitations given by Fig. 409 for 1 1/2 in. joint or weld throat thickness shall apply to all joints or weld throats of greater thickness.

(2) The sum of the greatest dimensions of porosity and fusion defects less than 1/16 in. in greatest dimension shall not exceed 3/8 in. in any linear inch of weld.

(3) Undercut shall not be more than 0.01 in. deep when its direction is transverse to the primary stress in the part that is undercut. Undercut shall not be more than 1/32 in. deep when its direction is parallel to the primary stress in the part that is undercut.

(4) Convexity or reinforcement of a weld face shall not exceed the limits shown in Fig. 408C and 408E [Figs. 2C and 2E herein] and there shall be no overlap.

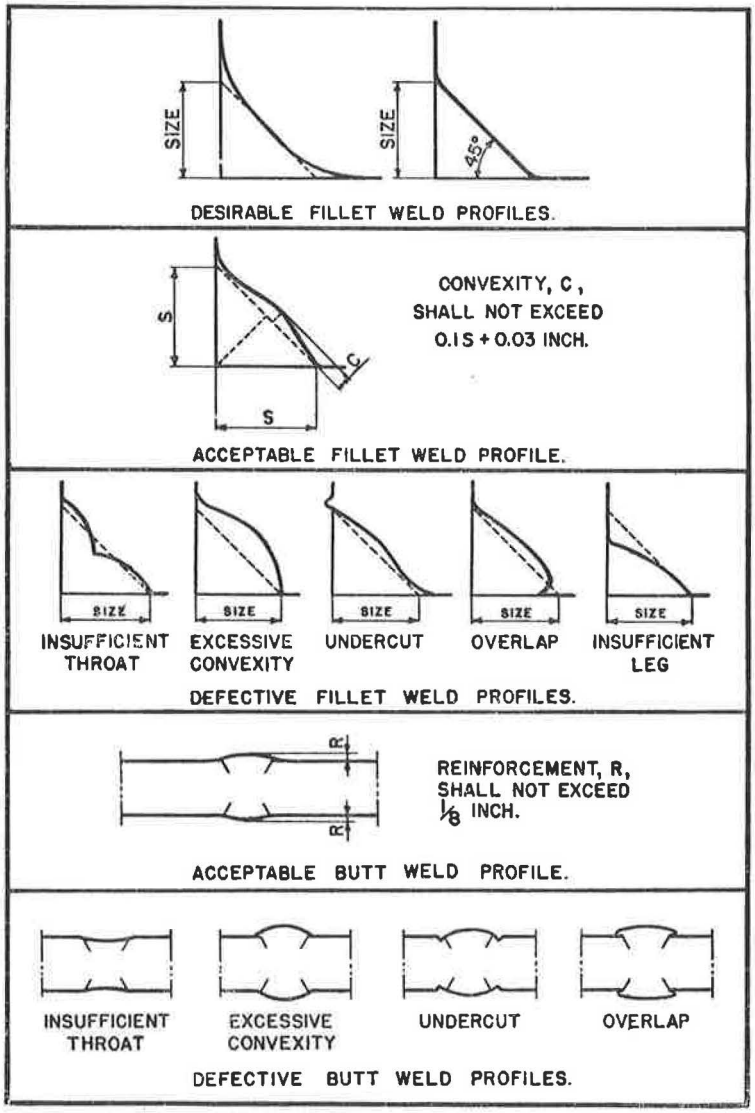

Figure 2. Weld profiles.

To restate these requirements more concisely: the weld must be free of visible and hidden defects as defined.

Visual inspection is a commonly utilized method of weld quality control. It constitutes the most practicable means for detecting visible defects. Defects pertaining to weld profiles or contours (Fig. 2) are easily observable. Fine surface cracks are revealed by means of devices such as strong lights and magnifiers.

As for the detection of hidden defects, code implementation is not clear. It is required that the welds be free of such defects, but tests needed for the purpose are not made mandatory. These are the so-called nondestructive tests, including the magnetic particle method, dye penetrants, ultrasonic testing, and radiography. It is stated, both in the Building and the Bridge Specifications, that such tests may be required to be conducted at the owner's expense. Testing cost could be considerable, but

more important is the eventual controversy connected to the evaluation of the test results. This is especially true when the device is radiography, which is the most thorough method for probing concealed weld defects. The revelation of the films is very much like opening Pandora's box. When applied to the framings of buildings, all such tests and consequent repairs invariably end up in litigation.

Present code requirements for weld quality are much too rigid for a reasonable assurance of adequacy. This is particularly true for the Building Code, which is concerned with structures designed for normal service loading where no fatiguing stress conditions prevail. In such applications some weld defects, such as possible inclusions, gas pockets, and even minor fusion faults, may be safely overlooked, without fear of impairment of structural adequacy. Radiography will reveal that defects of this nature are present in most all welded framings, yet the service performance of these structures, extending over periods of three decades or more, has amply demonstrated their dependability and strength. Therefore, at least in framings for buildings and other structures under similar loading, good visual inspection should generally suffice to assure an acceptable quality of welding. Only in instances where excessive cracking is observed should supplementary probing be undertaken. In such cases, use of magnetic particles or dye penetrants may be more dependable for disclosing the true extent of cracks prior to the needed repairs.

Use of ultrasonic testing and radiography should be confined solely to testing the soundness of welds in joints where cyclic stresses in the fatigue range would occur. Even in such applications, great care should be exercised in determining the extent of probing and in evaluating the importance of the revealed defects.

The economy of welded construction, and hence the scope of its utilization, is greatly dependent on code requirements. Extreme conservatism and needless restrictions in the form of unrealistic welding tolerances would limit the use of the technique and the profit to be obtained from its applications. The desired objective, the adoption of liberal welding tolerances consistent with safety, can only be achieved by close cooperation between code authorities and the various segments of the welding industry. Educational programs as well as pertinent research can play an important role in this task.

Review and Recommendations

I. O. JAHLSTROM, California Division of Highways

•IN HIS opening remarks, Mr. Scurr has correctly stated that the huge expansion of plant and personnel required by the magnitude of the Interstate Highway Program

> . . . has undoubtedly contributed to a condition which resulted in imperfections in construction that might not have occurred in a normal program. The public and political interest inherent in such a program has probably resulted in a tendency to magnify some of the imperfections out of proportion to their real significance in producing a satisfactory finished product.

Mr. Scurr points out that if a "tolerance curve" or a "statistical approach" to determine the limits of what is acceptable or not acceptable is to be established, research would be necessary to determine the limits for unquestioned acceptance, qualified acceptance subject to correction or penalty, and absolute rejection. He calls attention to the proposed AASHO Guide Specifications 105.3, Conformity with Plans and Specifications, stating that the intent of this clause "reaffirms the principle of exercise of engineering judgment." However, he states this does not give the inspector any reassurance or protection when his judgment may be questioned. "Only a statistically developed range of permissible tolerances can give such assurance."

Mr. Amirikian has very ably outlined the tolerances in welded construction. These are dimensional (warping, alignment, and fit), and welding tolerances (quality and acceptability of welds). Dimensional tolerances are specified in the AWS Code for Buildings and for Bridges and do not cause any problem. In fact, advances in welding technology may even permit a reduction in these tolerances. Problems in welding tolerances arise from the definition of an acceptable weld and development of inspection methods to assure acceptable welds.

Questions concerning inspection methods can be separated into two categories: (a) inspection of visible defects and (b) inspection of hidden defects. Mr. Amirikian feels that inspection of hidden defects is not clearly implemented in the codes. The code limits internal defects but does not specify the use of nondestructive tests for detecting the internal defects nor methods of evaluating the results of such tests. According to Mr. Amirikian, it is this matter of evaluation, particularly where radiographic testing is concerned, that leads to the greatest amount of controversy and litigation. In his opinion the present codes are too rigid. He feels that good visual inspection should suffice for buildings, and supplementary inspection should be utilized only where excessive cracking is observed. Magnetic particles and dye penetrants are most satisfactory for such cases. He feels that the use of ultrasonics and radiography should be confined to testing welds subject to cyclic stresses.

Mr. Amirikian feels the present code requirements are needlessly restrictive on the utilization of welded construction and that more liberal tolerances can be safely allowed if code authorities and industry will cooperate in researching tailored codes and educating designers to use them. We would question his broad statement: "Present code requirements for weld quality are much too rigid for a reasonable assurance of adequacy." What is "a reasonable assurance of adequacy" for a building where life and property are in jeopardy?

Mr. Amirikian is also concerned with, and seems to be trying to discourage, the application of radiography to building construction. We believe the fault is not in the radiographic codes but in the application and interpretation of radiographs. This fault

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can only be overcome by proper training and good experience of the radiographic technician, inspector, and engineers. Radiography has contributed more toward improving the quality of both the base material and the weld deposit than any other nondestructive method or combination of methods of testing used in present inspection procedures. Use of radiographic inspection in building construction or any other field should be limited to those applications where evaluation of radiographs is practical and in accordance with the governing code.

The writer cannot agree with Mr. Amirikian that weld defects should be permitted in excess of the code. Welding methods and design used today place a greater responsibility on the weld, welder, inspector, and engineer than it did 30 years ago. It is very true that great care should be exercised in determining the extent of probing and in evaluating the importance of the revealed defects. Therefore, the welding inspector should be experienced and qualified to evaluate the deficiency and the extent of repairs necessary.

The writer agrees with Mr. Amirikian that welding tolerances should not be unrealistic and that any adopted tolerances should be consistent with safety. However, it should be emphasized that it is as equally important to have qualified inspectors as it is to specify qualified welders and welding procedures. One without the other will not achieve the objective of economic and safe welded construction, regardless of tolerances in the code.

Mr. Moss calls attention to the cooperative work of ARBA and BPR committees in advocating the use of a statistical approach in the analysis by acceptance tests of materials and performance in highway and bridge construction projects. He outlines the problems today in highway construction and cites the application of statistical approach to problems in industry and on the AASHO Road Test.

No one engaged in highway and bridge construction will deny the need for proper tolerances for quality control. However, it is questionable whether standard deviation curves and standard numerical limits can be determined which will be workable throughout all the states. The trend appears to be to write everything into the specifications, but it is doubtful standard specifications can be written which will be uniformly applicable in all the states under varying job and climatic conditions and will virtually eliminate the necessity of on-the-job decisions by the inspector and the engineers.

Perhaps we are hoping to arrive at Utopia too fast for the present system. Even with the statistical approach skilled and well-qualified inspectors—the same type of inspectors and engineers who had the engineering know-how to build good roads and bridges in the past—will still be required on the job. We have good men on the jobs. By backing up these men, weeding out the nonperformers, and displaying a little more "rugged individualism," we can continue to turn out good work.

This is not to say we should not improve, revise, and discard, if necessary, obsolete and unworkable specifications. The states are continually doing this. We should approach this problem in the same way we plan and design our highways and bridges—by careful review of the problem, taking into consideration all the aspects and factors involved to arrive at the best solution.

Mr. Lyman presents some very interesting and pertinent comments from several well known bridge engineers on construction tolerances for prestressed concrete. The AASHO-PCI Manual for Inspection of Prestressed Concrete referred to is an excellent guide for prestressed concrete construction.

Mr. Dean's summation is worth repeating:

> The published tolerances are not to be considered forever binding.... Improvements and modifications will surely be developed; any set of dimensional tolerances should be applied with judgment and some understanding of member function.

We agree with the comments on camber and that further study is needed on this problem, particularly ultimate camber. Dimensional tolerances do not present much difficulty in established fabricating plants. Problems at bearing seats are minimized by use of elastomeric bearing pads. These will absorb up to $\frac{1}{8}$-in. twist in the bearing surface.

A good point is made by Mr. Thurman: "With allowable tension under full design loads, I feel that the accuracy of the prestressing force assumes more significance than previously." In California, we think we are achieving better accuracy in stressing the tendons with load cells developed by our Materials and Research Laboratory.

We do not concur with the idea of penalties for a secondary range of tolerances. This could be a very controversial matter. The penalty, if there is this provision in the specifications, should be harsh enough to discourage continued infraction. Generally, the remedial work is minor and the member can be restored to full structural value. If the structural adequacy of the member is questionable, it should be discarded.

The information and data collected by Mr. Lyman, together with the results of studies now under way by the PCI, should help to provide more realistic and workable tolerances in prestressed concrete.

Defining concrete as a "manufactured" material, Mr. Anderson states "the application of scientific tolerancing in concrete construction has not been considered to any extent in engineering or design procedure." This lack of tolerance information, he says, has led to misunderstanding and controversy. Characteristic of designs of the past cast-in-place structures were conservative working stresses and adequate margins of safety.

"Qualitative and quantitative tolerancing will become a part of the engineering and design procedure," Mr. Anderson says. The present trend toward ultimate strength design using higher stresses, lighter sections and high-strength steels will demand greater precision of concrete manufacturing and workmanship.

Tolerances are necessary in concrete construction, Mr. Anderson states, in relation to integrity and safety of the structure, aesthetics or appearance of the work, and economics, involving cost to owner, designer, or contractor.

On the subject of structural intergrity, Mr. Anderson begins with the "manufacture" of concrete and points out the influence of manufacturing tolerance on concrete quality. He refers to a paper by Mr. Abdun-Nur in the ACI Journal of January 1962. This paper presents cogent arguments for a specified tolerance in concrete strengths. We agree with Mr. Anderson that a minimum strength concrete is not a realistic specification and is not being met. The advancement of precast construction with higher stresses and thinner sections requires better and more realistic controls. In regard to dimensional tolerance we agree wholeheartedly that poorly constructed forms will not give dimensional integrity and will increase costs.

With strict interpretation of specifications, exercise of engineering judgment will not be acceptable practice. Tolerances must be established that are practicable and will insure quality work. Mr. Anderson summarized suggested tolerances by ACI for conventional concrete bridges and for precast concrete construction. A more liberalized table of tolerances proposed by precast manufacturers is also given. Any proposed tolerances will be considered too restrictive by some, at least in part, and too lenient by others.

It will take time for observation, study, and comparison to arrive at practical and workable tolerances acceptable to everyone.

Mr. Anderson's paper is thought provoking and, from his background of experience, offers practical suggestions for improving bridge specifications in regard to construction tolerances.

With the availability of various good form materials and with any kind of desire to produce good work there should be little need for tolerances in bridge specifications on surface appearance. How long will a concrete surface on a bridge remain uniform in appearance?

In summation, we believe we do not have to sacrifice quality to determine practical and reasonable limits or tolerances.