THE EFFECT OF CONSTRAINT ON FRACTURE SAFE DESIGN

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A fracture safe design can be influenced by constraint. The analysis of failure in a structural component depends on two inputs, the fracture behavior and the deformation behavior; both depend on constraint. Current work has concentrated more on looking at constraint effects on the fracture behavior, and in particular, brittle fracture. This addresses only half of the constraint problem. Concern must also be given to the effect of constraint on deformation behavior, especially in the nonlinear region of behavior.

INTRODUCTION

Constraint is an important issue in the use of a fracture mechanics approach for developing fracture safe design criteria. It has often been observed that the transferability of laboratory test results for the prediction of fracture behavior in structural components was not always very successful. One problem is that the constraint of the laboratory specimen did not match that of the structural component. In the past tools were not available to account for constraint in fracture prediction. The one parameter fracture mechanics approaches that have been used for decades did not account for constraint differences in the various sizes and geometries of laboratory specimens and structural components (1, 2, 3). With the recent development of the two-parameter fracture mechanics, a tool is available to account for these constraint differences (4 - 7). The two parameter fracture mechanics methodology is applied principally to the prediction of fracture behavior in the transition for steels (5, 7). This does not account for all of the areas of prediction that are controlled by constraint.

The prediction of failure in structural components requires two separate pieces of information (8, 9). One is the fracture behavior; that is information about the

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point of fracture or the process of fracture in terms of a fracture mechanics parameter. The other is information about the deformation process that the structure is undergoing while it is in the process of fracturing. For example the fracture behavior can be characterized in terms of K_{Ic}, J_{Ic}, δ_c, or an R curve, but an exact knowledge of this characterization does not give the design parameters such as failure load, displacement, stress or strain. To specify these design parameters requires additional information about how the component deforms under loading; this deformation information is separate from the fracture characterization. These two pieces of information, the fracture behavior and the deformation behavior can be combined to predict the design parameters that characterize the fracture behavior in the structure (9).

The current two-parameter fracture mechanics approach specifies the fracture characterization in terms of a fracture parameter and a constraint parameter. Examples are the K-T approach of linear-elastic fracture (4) or the J-Q approach for elastic-plastic fracture (5, 6, 7). In most cases the constraint parameter is used as a second correlating parameter for characterizing fracture. For example, a J-Q fracture locus would be given rather than a single value of J for fracture (5). To get a better prediction of fracture behavior, the constraint parameters can be used in mechanistic based fracture models (10). The current constraint parameters give information about the crack tip stress field. Therefore, they have been more successful in correlating stress controlled fracture behavior, such as brittle cleavage, than for strain controlled fracture, such as ductile R curve fracture. Work to look at the effect of constraint on ductile fracture has recently been successful (11), but this work relies on detailed numerical analysis and has not produced easily identifiable parameters that the experimentalist or designer can use.

However, all of the work on constraint has emphasized the fracture event itself and not on the deformation process. Since the deformation behavior is also needed to predict structural behavior in terms of such things as failure load, the effect of constraint on deformation is also an important factor. Recent work by Donoso and Landes (12) has considered the effect of constraint on deformation separately from the fracture concern. This provides additional information needed to determine the effect of constraint on fracture behavior; however, a complete methodology to relate the effects of constraint on all types of fracture behavior is not yet available.

This paper will discuss the issues relating to the effect of constraint on fracture safe design. Formats for combining the effects of constraint on both the fracture behavior and the deformation behavior will be discussed. This will be done for both ductile and brittle fracture behavior and both linear elastic and elastic-plastic deformation.

PREDICTION OF STRUCTURAL BEHAVIOR

Two pieces of information are needed to make a prediction of the failure behavior in structural components containing defects (9). They are the deformation behavior of the structure and the fracture behavior. The deformation behavior gives the relationship between load and displacement of the component or an analogous relationship such as stress and strain. It is usually done independently of the fracture behavior but is done with the inclusion of the effect of the defect. Deformation behavior usually combines a linear-elastic and an elastic-plastic contribution. The fracture parameters are also determined from the deformation behavior of the structure and would include a combination of a linear elastic term, usually K based, and an elastic-plastic term, usually based on J or, δ. The deformation behavior may be essentially linear elastic, in which case the elastic-plastic term makes no significant contribution, or elastic-plastic in which case both terms contribute. The deformation behavior usually requires a knowledge of the tensile properties of the material in the structure. The solution to the deformation behavior may come from analytical or numerical analysis (9, 13), from a solution in a handbook (14), or better yet can be inferred from the deformation of the fracture toughness specimen (9, 15).

The fracture behavior of the structure specifies what happens to the defect in the structure. The fracture process can be labeled as being brittle in which case the defect grows rapidly and in an unstable manner and the fracture behavior can be characterized as occurring at a single point with a single value of the fracture parameter giving the fracture toughness. Alternatively, the fracture can be labeled as being ductile in which case the fracture occurs as a process during which the defect grows in a stable manner and the fracture is characterized by an R curve rather than at a single point. Predicting the behavior for the structure involves a combination of the deformation behavior with the fracture behavior. For the case of brittle fracture the analysis is easier. The deformation process, which entails a monotonic increase of load and displacement, continues until the point of fracture at which point the deformation terminates and the load at the point can be taken as the failure load. For ductile fracture the deformation is influenced by the stable crack extension. Most methods of analyzing the ductile fracture behavior of a structure consider that the stable crack growth changes the deformation process by continually changing the crack length of the component. The two processes are usually analyzed as uncoupled behaviors that must be combined. For example, the R-6 approach (16) uses a normalized diagram to specify the deformation process and fracture parameter calibration. The toughness values are plotted to see where they fall relative to the deformation and fracture calibrations. The EPRI Handbook (14) takes the deformation and fracture calibrations from a handbook compilation and the toughness is input separately in a manner not specified in the Handbook. The Engineering Treatment Model (17) uses calibration functions in which load is normalized by limit load and toughness is input at a point. The ductile fracture methodology (9) uses a similar normalized approach and treats the ductile fracture characterization as a procedure to keep account of the current crack length which in turn modifies the deformation behavior.

For all of these methods the deformation behavior plays an important role in determining the maximum load attained or the failure load. The deformation process and fracture parameter calibrations are influenced by constraint. It is therefore important to determine the deformation behavior and fracture parameters as a function of constraint. In the past this has been done by specifying the constraint as being plane strain or plane stress (14). This allows only two extreme constraint conditions to exist. In fact actual constraint is usually somewhere between these two extremes. Often a plane strain constraint was used and the analysis done in this manner with the assumption that plane strain is conservative. In fact, the plane strain assumption is unconservative in the analysis of the deformation behavior of a component (12). Although plane strain is often conservative for fracture behavior, the effect of assuming plane strain on the combined analysis of deformation and fracture is uncertain and can often be unconservative.

EXAMPLES OF CONSTRAINT CONCERN

The manner and extent to which constraint affects the failure behavior of the structure depends on the type of fracture and deformation that are occurring. By considering the various types of behavior it is possible to make some evaluation of where constraint should be carefully considered, where it does not make as much difference and how to make conservative approximations. The typical deformation pattern of a component is shown in Fig. 1. The deformation here is plotted as load versus displacement but an alternate format could be used. In the early stages of loading the deformation is linear-elastic. The extreme effects of constraint on deformation in this region is reflected by its effect on the elastic modulus, E for plane stress and $E/(1 - \nu^2)$ for plane strain, where E is the elastic modulus and ν the Poisson's ratio. For metals with $\nu \approx 0.3$, the extremes of constraint effects are not more than ± 5% and are not very important. As the loading continues, the load versus displacement can become nonlinear as the component begins to undergo plasticity deformation. As this happens, the slope of the loading curve decreases and may eventually become nearly flat. In this region the load is not increasing very much and the increased deformation is manifest mostly as an increase of displacement or strain. For the case in Fig. 1, the defect is assumed to be stationary and the deformation curve continues to rise due to hardening.

In the nonlinear loading region; however, the constraint plays an important role. The magnitude of the load in the region of nonlinear deformation is strongly influenced by constraint. Using the constants in the EPRI Handbook and the extremes of plane strain and plane stress, the loads at a given displacement will be different by a factor 1.36 with the plane strain having the higher load. The effect of the lower constraint for plane stress is shown in Fig. 2 where the deformation curves for plane strain and plane stress are shown. As can be seen, the effect of the lower plane stress constraint during the linear loading is small; however, during the nonlinear loading the effect of the lower constraint is much greater. Since the plane strain constraint results in higher loads for the same displacement, a prediction of the failure load assuming plane strain constraint could greatly overestimate the actual failure load when the structural component has low constraint.

The effect of the fracture toughness on the deformation is shown in Fig. 3 using the ductile fracture model approach (9). For brittle fracture the deformation curve is abruptly ended. For ductile fracture the deformation curve is altered as the stable crack growth occurs. Ductile crack extension decreases the load at a given displacement in a manner proportional to the amount of stable crack extension. The usual result of this ductile crack extension is that the load reaches a maximum value and then decrease with continued displacement.

In the analysis of structural components the maximum load attained is often an important design consideration. The subsequent discussion of the effect of constraint will be made with the assumption that the maximum load attained is important. Since the fracture behavior and deformation behavior are relatively unrelated, the fracture event can occur in any region of the deformation curve. If fracture occurs on the linear-elastic region of the loading, constraint does not play an important role in determining the deformation behavior. However, the level of the fracture toughness is of extreme importance because the load and toughness are linearly related. Here the effect of constraint on fracture behavior is of the most importance. On the other hand if the fracture occurs on the nonlinear part of the deformation curve, especially where the loading versus displacement is relatively flat, the constraint plays an important role in determining the level of the load in the deformation behavior. However, the point at which fracture occurs is much less important since it does not much influence the maximum load attained.

Usual patterns of behavior cause brittle fracture to occur more in the linear elastic loading part of the behavior and the ductile fracture to occur in the nonlinear part of the loading. Hence, during the linear portion of loading, the effect of constraint on the fracture behavior is of the most importance and during the nonlinear portion of loading the effect of constraint on the deformation behavior is of the most importance. This is the usual pattern of behavior but it is not absolute because there are many exceptions.

Examples of the result of neglecting constraint are illustrated in Figs. 4 and 5. In Fig. 4 the structural component model is a large compact specimen. Fracture is assumed to be brittle and to have been measured as K_{Jc} = 278 MPa√m on a small compact specimen. On the large structure this toughness causes fracture to occur at a load of about 4600 kN, which is somewhat into the nonlinear region of loading. The toughness as measured on the small compact specimen is unconservative because the constraint is relatively low. If the constraint that the large specimen would have is included, the actual toughness should decrease to decrease K_{Jc} = 165 MPa√m. The resulting fracture load prediction is 2920 kN which occurs essentially in the linear-elastic region of loading. Thus ignoring the effect of constraint on fracture toughness causes an overestimate of the failure load by nearly 60 %.

In the second example the fracture is ductile. The component model is a large compact specimen with a small thickness. If the constraint of a thick specimen, plane strain, is used to predict the loading behavior of this specimen, the result is as shown in Fig. 5. Here the actual test data are shown with both plane strain deformation and fracture inputs and with plane stress deformation but plane strain fracture prediction. Since the specimen is completely plane stress, using both plane stress deformation and fracture would predict the actual test result. The plane strain assumption for deformation behavior gives an unconservative prediction in terms of maximum load attained by nearly 20%. Using plane stress deformation makes the prediction conservative. The plane strain fracture makes the prediction too conservative; however, the maximum load reached is not too far from the test result. This is because the fracture process begins on the relatively flat region of the loading where the maximum load reached is not much influenced by the toughness.

The examples in Figs. 4 and 5 show the extremes in behavior, the first is the case where constraint influences the fracture toughness significantly but not the deformation behavior. The second is a case where constraint influences the deformation and the influence on fracture behavior is not so important. Because the effect of constraint is relative to the type of behavior it is not possible to make general rules about its effect and each case should be analyzed to separately to look at the effect of constraint.

EFFECTS OF CONSTRAINT ON FRACTURE TOUGHNESS

The example in Fig. 4 shows that constraint effects on fracture toughness could be important in determining the maximum load at failure for a structural component. This is especially true when the fracture is occurring during the linear-elastic part of the loading. There are several ways to incorporate the constraint parameter into the prediction of fracture. The usual approach is to make a locus of toughness values, a K versus T or a J versus Q fracture locus (5). Combining a constraint prediction with a statistical evaluation of thickness effects (18) provides a tool that can be used to adjust the fracture toughness determined from a laboratory test at one level of constraint so that it can be used to predict the fracture level of a structural component that is at another constraint. The problem with this approach is that most materials have not be tested in enough constraint conditions so that a reasonable fracture locus can be determined. Developing a reasonable data base for steels in the transition would be a formidable task because many specimens tests would be required at each constraint level to deal with the problem of statistical scatter.

To make predictions of fracture toughness at one constraint level from tests conducted at another constraint level would require a model of the brittle fracture based on these constraint effects. The author has recently developed a model based on crack tip stresses field as modified by constraint and a weak link initiation mechanism for fracture (19). This model can use fracture toughness measured at one constraint level to predict toughness at a different constraint level. The model can be applied, for example, to predict toughness at one temperature from toughness measured at another temperature. This application is not very useful because tools such as the master curve concept has already been able to do this (20, 21). A more useful application of the model is to predict toughness measured on a specimen type geometry to predict toughness on a completely different geometry such as a structural component geometry. Results from the model show that the a completely accurate prediction has not been achieved but the trends of the prediction are correct (10, 19). Particularly the trend of toughness at the end of the transition where the brittle fracture changes to ductile fracture has been predicted (19). With further development the model could be used to predict fracture behavior at different constraint levels without the need for extensive testing.

The effect of constraint on the ductile fracture behavior has not been as successfully predicted by the two-parameter fracture models as was the brittle fracture. This is because the ductile fracture behavior is predominantly strain controlled. The two-parameter models predict the effect of constraint on the crack tip stress field and stress controlled brittle fracture is more influenced by the stress change accompanying constraint change than is the strain controlled ductile fracture. Recent work by Xia and Shih (11) has used a numerical analysis method with a material that is modeled as initiating and propagating voids in the manner of the microscopically observed ductile fracture process. The results of this numerical analysis has been able to predict the effect of different geometries and modes of loading on the resulting R curve as characterized by J. The model is not yet developed to the point where the constraint for different geometries can be expressed in terms of simple engineering parameters like the ones used for brittle fracture; however, it does give that promise for doing that in the future. Fortunately, the ductile fracture process usually occurs at a higher toughness level and consequently can occur on the nonlinear part of the deformation curve where the level of toughness does not have as much influence on the maximum load reached. Therefore, for ductile fracture it is usually more useful to look at constraint effects on the deformation behavior.

EFFECT OF CONSTRAINT ON DEFORMATION

The effect of constraint on the deformation is important, especially when the fracture event or process occurs on the nonlinear part of loading. For many of the fracture related problems in structures this can be the most important influence of constraint because it is more likely that a material will be chosen to be in the regime of ductile fracture rather than brittle fracture. Unfortunately the effect of constraint on deformation behavior is not studied nearly as much as its effect on fracture behavior. In many cases where constraint effects are considered for deformation behavior the EPRI Handbook is used (14). Here constraint is determined for the two extremes, plane strain or plane stress. The difference between the two can be fairly large as shown in Figs. 2 and 5 and can have an important influence on the maximum load that may be reached in the structure. As stated previously, plane strain predicts a higher maximum load and is not conservative. The plane stress deformation could be used as the conservative case but it is often enough different from plane strain that it may be overly conservative. The more recent work on three-dimensional numerical simulation of deformation behavior should improve the ability to predict the effect of constraint; however, to date not many solutions are available in the literature.

Recent work by Donoso and Landes (12, 22) has considered the effects of constraint on deformation The approach they used to characterized the deformation process by three separable functions that are multiplied together. The previous work of Ernst (23) and Sharobeam and Landes (24) showed that the general deformation pattern could be characterized by two separable functions, a geometry function and a deformation function multiplied together. The approach of Donoso and Landes takes an additional step by adding a third function, the constraint function. The general character of the load versus displacement function is

$$P = \Omega \, G(a/W) \, H(v_{pl}/W)$$

where G(a/W) is the geometry function, H(vpl/W) is the deformation function and Ω is the constraint function. Simple formulations have been suggested and verified for the G and H functions (9). The Ω function has been in the past determined experimentally (12); however, giving it the extreme values of plane strain or plane stress has worked fairly well for specimen type geometries. It was found that predominantly bend specimens like the compact or single edge bend had a large range of constraint which depended on the shape of the remaining uncracked ligament, b/B, where b is the uncracked ligament length and B is thickness. An example for these specimens is shown in Fig. 6 where the constraint factor, Ω, is plotted as a function of b/B. For the long and thin ligaments, b/B > 1 the constraint factor tended to the plane stress value as defined in the Handbook (14). For the very long ligament shown in Fig. 6, Ω even goes below the plane stress constraint value. For the short and thick ligaments the Ω tended toward the plane strain value but never really reached it.

For the predominantly tension loaded specimens, like the center cracked tension specimen, the constraint factor tended toward the plane stress value for all thicknesses (22). For the latter case there are not many examples available in the literature so that a thorough evaluation could not be made. If tension geometries all tend toward having plane stress deformation constraint, it is important to know so that unconservative failure loads are not predicted from using the wrong assumption for constraint. Many structural components resemble the tension loaded cases more than the bend geometries.

It is obvious from these few examples that the constraint effect on deformation cannot simply be determined by assuming one of the extreme values, plane strain or plane stress. Worse yet, arbitrarily choosing a plane strain value for constraint is not conservative and will nearly always cause an overestimate of the failure load. It will be important to put more effort in the future into the study of constraint effects on deformation.

SUMMARY

To properly evaluate the effect of constraint on a fracture safe design, the effect of constraint on both fracture behavior and deformation behavior must be considered. The effect on fracture behavior is of most concern for fracture that occurs in the linear-elastic loading region for the structural component and the effect of constraint on deformation is of most concern in the nonlinear region of loading. However, the interaction of the fracture behavior and the deformation behavior can be complex so that general rules cannot be made to cover every case and each case should be separately analyzed. Present work to study constraint effects has concentrated most on brittle fracture in the transition. This is an important area of concern but addresses only half of the problem associated with constraint effects on a fracture safe design. Additional effort is needed on the effects of constraint on deformation behavior during the fracture process.

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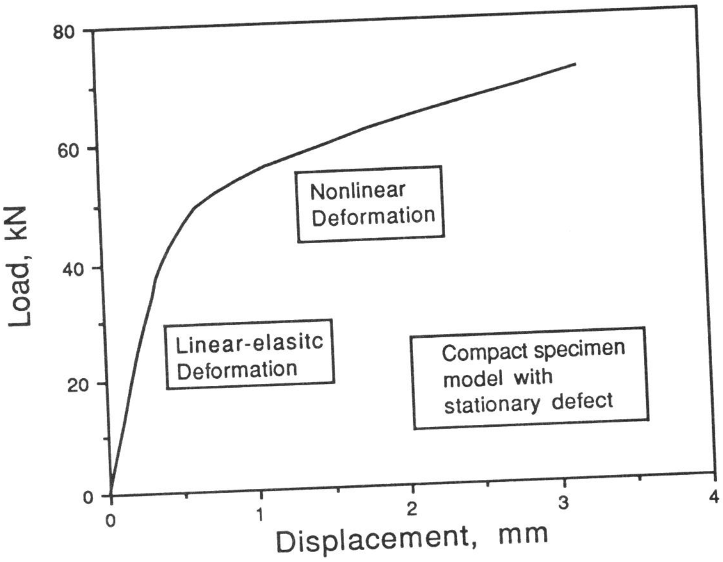

Figure 1. Typical Load vs. Displacement Deformation Curve of Structure with Defect

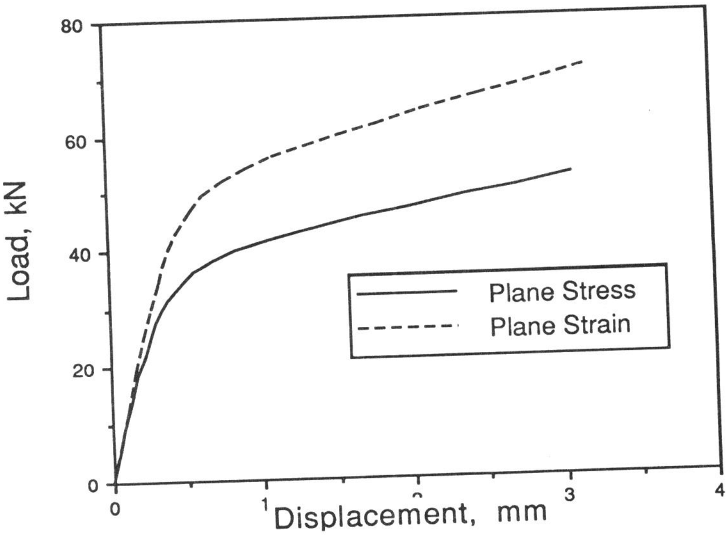

Figure 2. Load vs. Displacement Contrasting Plane Stress and Strain Deformation Constraint

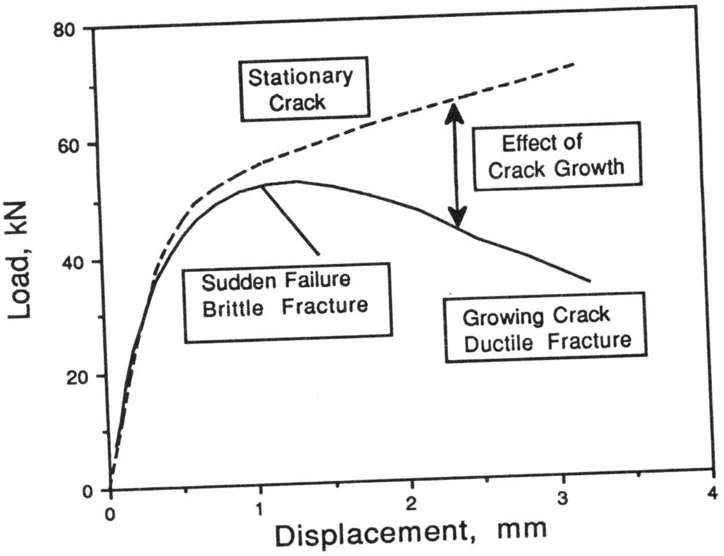

Figure 3. Load vs. Displacement Showing Effect of Growing Crack

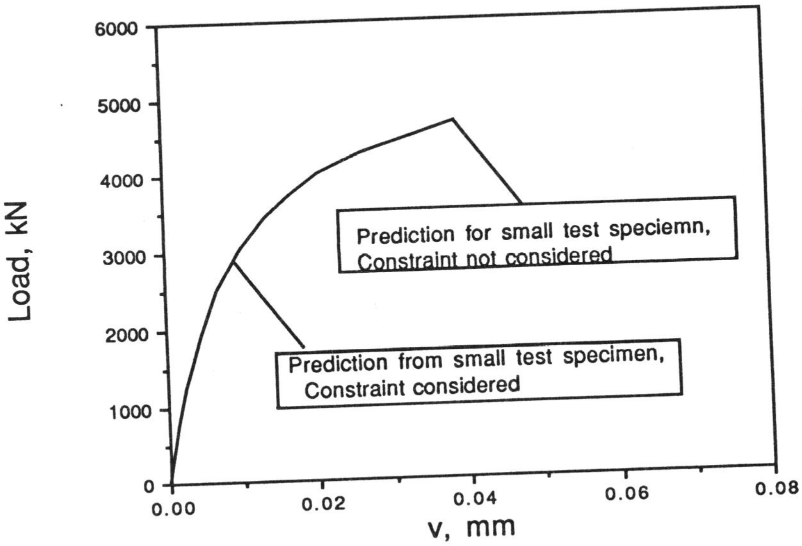

Figure 4. Failure Prediction with and without Constraint Consideration

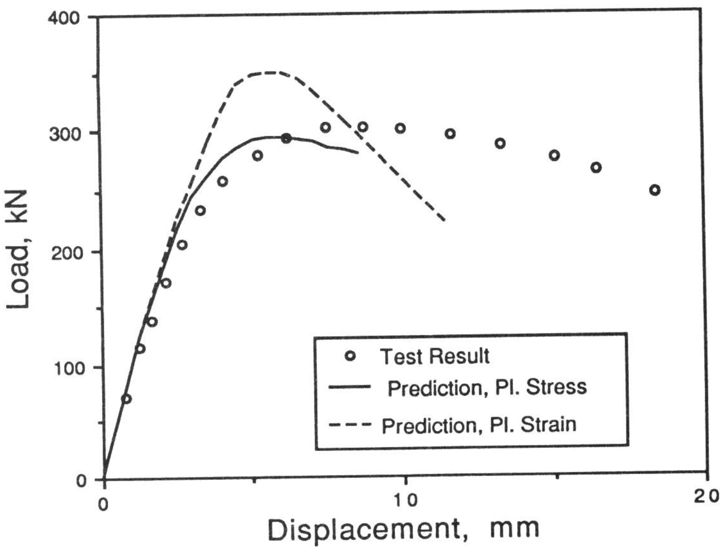

Figure 5. Plane Strain and Stress Predictions of Thin Specimen Test Result

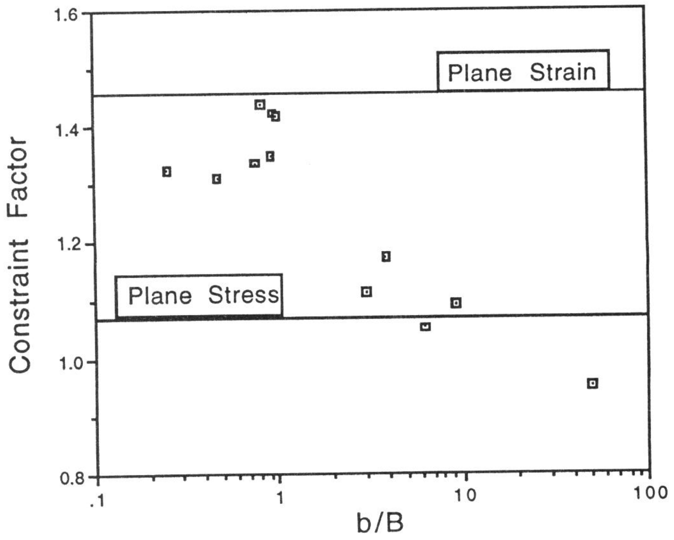

Figure 6. Constraint Factor vs. b/B for Steel Compact Specimens