Fatigue Behavior and Analysis of Welded AlZnMg Joints

Analyses of fatigue data are carried out systematically with several aluminum alloys for a variety of joint types typical in structural engineering

BY DIMITRIS KOSTEAS

ABSTRACT. Extensive statistical and regressional analysis of fatigue data has been carried out systematically for a variety of joint types with several aluminum alloys typical in structural engineering. Complete P-S-N curves in linear-log or log-log coordinates in the medium and high cycle range have been established, enabling a definition of safety factors on terms of reliability.

The data serve as a background for the development of a standard on fatigue behavior of welded aluminum joints on a national/European basis; they also serve as a reference for further experimental work trying to establish a method for the fatigue life prediction of aluminum weldments on terms of crack initiation and propagation. This paper presents the results of a study with welded AlZnMg (comparable to AA 7005) joints. An effort is undertaken to present results on a unified basis of slope and scatter which may allow an extrapolation to other joint types or alloys.

Introduction

About a decade ago new efforts were undertaken in Europe to develop comprehensive standards for aluminum structures, especially for the now widely used welded aluminum alloys. This led to a number of national standards, most of which deal with the problem of static loading only or do not cover the whole spectrum of different alloys, notch cases, etc., as they actually appear in service. Moreover, differences in testing procedures and evaluation methods led to contradictory results several times. Similarly, the definition of allowable stresses for design purposes came about more or less arbitrarily, depending to a large extent on personal experience.

With a number of research programs conducted internationally by the Centre International de Développement de l'Aluminium (CIDA), studies on the fatigue behavior of aluminum alloys over a large range in terms of fatigue life were initiated in the 1960's. In a series of further programs, the fatigue behavior of welded aluminum joints has been studied for several joint types and alloys, plate thicknesses, welding parameters, etc. At the Laboratories for Steel, Wood, and Stone of the Karlsruhe University in West Germany, more sophisticated methods of analysis have been used in order to reach a certain degree of reliability for specimens and structural components. A compilation of data for relevant cases in service was undertaken a few years ago together with comparative studies. A similar development was initiated in the United States based on activities and recommendations of the Aluminum Alloys Committee of the Welding Research Council; several reports have already been presented.[1,2]

Data from fatigue tests performed in Europe have been accounted for only minimally (if at all) in these investigations. Especially in the case of Western Germany, there have been considerable efforts to close the gaps in fatigue test data for relevant cases in engineering practice and to analyze these results with the objective of developing a code practice for cyclically loaded aluminum structures. The Aluminium-Zentrale in Düsseldorf, Germany, functions as a coordinator of these activities which are performed mainly at two research institutions; it also coordinates work on both a national (i. e., with the German Standards Organization, DIN) and international level (European Convention for Constructional Steelwork, Comm. 16 on Aluminium Alloy Structures).

This paper summarizes pertinent investigations and their results and outlines the guidelines along which a future code of practice may develop. The data are confined, for reasons of perspicuity, to AlZn4,5Mgl alloy weldments only; this alloy type is used in Europe mainly and has not been covered thoroughly by similar American investigations. Details of the studies used here and data on other alloys are reported in the literature,[3-6] and there have been numerous further references and individual project reports.

Scope of Investigation

In dealing with aluminum weldments, a serious problem is presented by the numerous different structural alloys to be considered. Each alloy shows a different stress-strain-relationship which will again be different in the case of a welded structure, with at least three distinct regions—weld, HAZ, and unaffected base metal (Fig. 1). Fatigue experiments have been time-consuming and costly, and a more than perceptible scatter has affected the interpretation of results.

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DIMITRIS KOSTEAS, formerly a Professor and Head of the Department on Fatigue, Laboratories for Steel, Wood and Stone, Karlsruhe University, is now with the Technical University of Munich, West Germany.

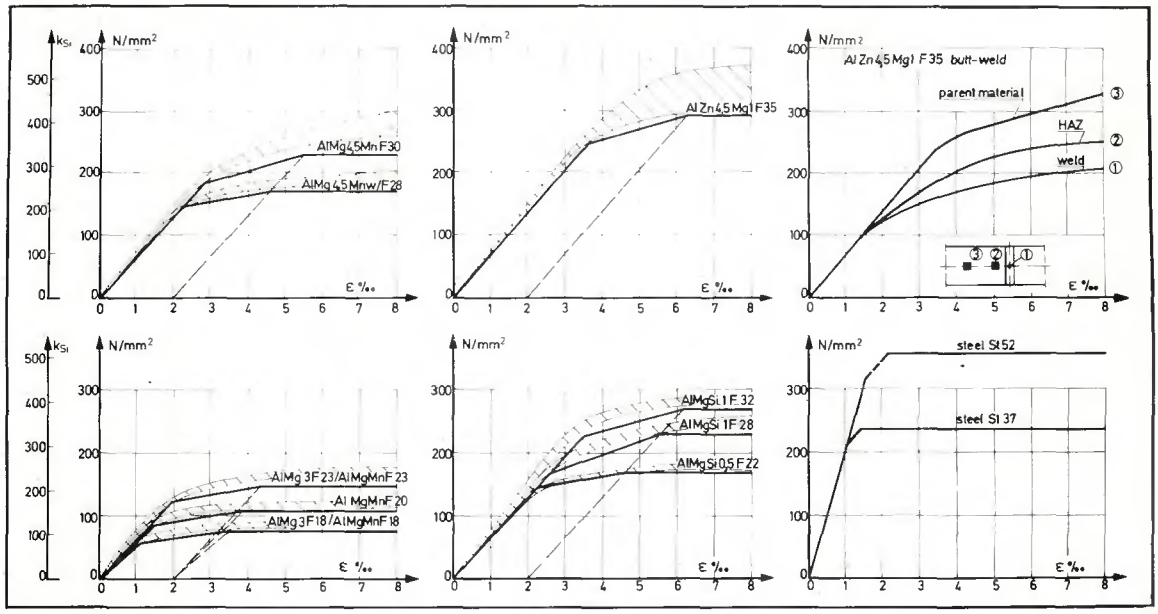


Fig. 1—Aluminum alloys/stress-strain behavior (scatter band experimental results/secant line relationship)

These factors led to the decision to concentrate efforts on data concerning the three most interesting standard aluminum alloys after the new German code DIN 4113 (Fig. 2) and also three common joint types:

1. Alloys—AlZn4,5Mgl; AlMgSil; AlMg4,5Mn.
2. Joint types—plain plate, as reference upper limit value; transverse butt weld; transverse load-carrying fillet welds (cruciform)

The whole program actually included three additional welded joint types (Fig. 3). However, experimental investigations with the three alloys listed above are carried out as transverse butt welds or transverse fillet welds only.

It is not the aim of this paper to go into detail about the fatigue behavior of the three above alloys or joint types or of the many factors influencing the weld fatigue life. These factors have been described quantitatively before[1,2,7] and lead to similar conclusions about the effect of geometrical joint details, weld reinforcement, weld imperfections or defects and environment. It is, rather, one purpose of this paper to outline certain guidelines along which analytical procedures in defining S-N curves will have to proceed in the future, allowing a universal approach for aluminum alloys and joint types, the latter being correlated on the basis of actual maximum stress at the critical site. Another purpose is to point out underlying assumptions in efforts to define a new comprehensive code of practice for welded aluminum structures under repeated loading conditions.

For purposes of this paper, data are restricted to AlZn4,5Mg1 alloy joints, and to reserve butt welds mainly. This alloy corresponds to AA 7005 or, as it is currently defined in the European design code, to 7020 (Table 1). Several hundred test results have been analyzed,[6] for instance about 500 tests on transverse butt welds between 4 and 20 mm (5/32 to 25/32 in.) plate thickness, with square or single V groove welds up to 14 mm (18/32 in.) and double V groove for thicker plates, GMA welded.

Test results concentrate mainly on R = −1 (reserved stress) or 0 (0-tension stress). The main area of interest here is on the intermediate cycle fatigue range, i. e., between 10^3 and $2 \cdot 10^6$ cycles approximately. The high cycle range has been investigated separately by means of the stair-case and probit methods for tests at $2 \cdot 10^6$ or 10^7 cycles.

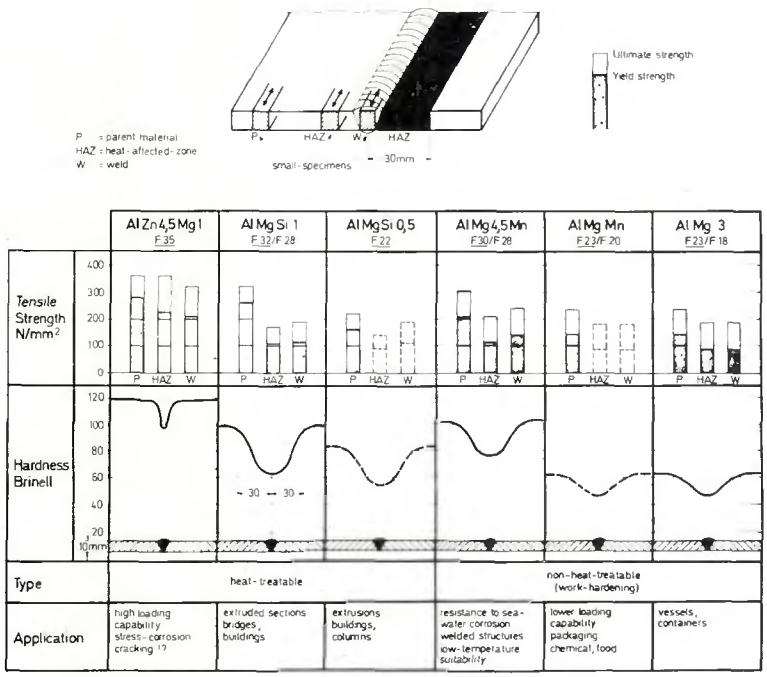
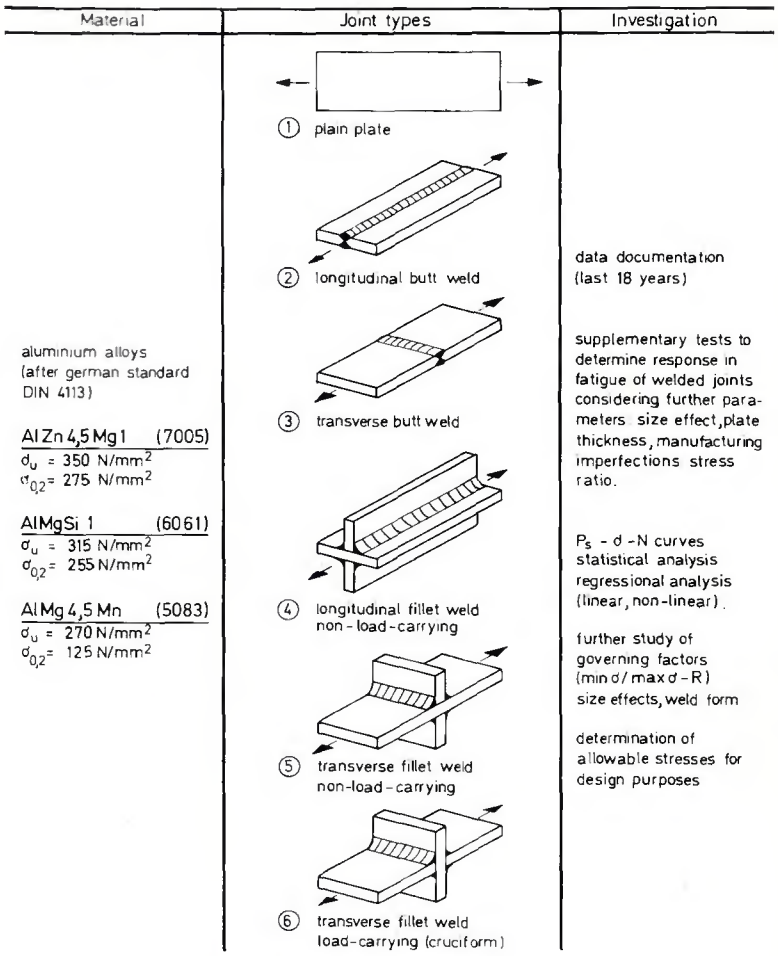


Fig. 2—Aluminum alloys (after German standard DIN 4113)

Data Analysis and Presentation

The methodology of statistical analysis has been explained adequately before.[6,7] In a first effort, our aim was to use a simple, efficient analysis, with no a *priori* assumptions, being universally applicable on tests with laborato-

Fig. 3—VA/DFG program 75-76 for aluminum alloys—scope of investigation



ry specimens and structural components as well. Even though multiparametric S-N-relationships have been analyzed, preference is to be given to linear functions in the intermediate cycle range for obvious regions.

The log-log BASQUIN-type function $\log N = k \log S + b$ is used now almost exclusively for analytical purposes. This is because it has the advantage to provide a link between S-N-curve studies and fatigue life predictions based on low cycle fatigue crack initiation concepts and fracture mechanics crack propagation principles. This type of regression analysis leads to a bundle of best fit S-N-curves for different values of probability of survival P_s and confidence level γ (Fig. 4), and is often accompanied by a confidence band for the mean S-N-curve (Fig. 5).

Most available test results have been in the middle part of fatigue life, roughly between 20,000 and 1,000,000 cycles. For relatively short or relatively long lives there exist (especially for joint types other than butt welds) only very few reference points. Regression lines have been extrapolated up to fatigue lives of $2 \cdot 10^6$ cycles in a first approximation and attempt to bring these values in some relation to previous experience with steel. This has been done even though it has been shown in comparative studies of two- and multiparametric regression curves that the first tend to overestimate fatigue life at about 10^5 cycles and then clearly underestimate it over 10^6 cycles.

There appears to be no significant difference in slope of regression lines between the two types of loading (reversed and zero-tension). This is also true for individual test series, at least within a certain weld form. Reassuring and helpful for further generalizations is the fact that a fairly constant stress ratio T_S or life ratio T_N, as an expression for the width of the scatter band, has been computed. Note for instance the values $T_S = 1 : 1.35$; $T_N = 1 : 3.09$ for 10^5 cycles and $T_S = 1 : 1.73$ for $2 \cdot 10^6$ cycles respectively (Fig. 5).

Difficulties are sometimes encountered in including individual test results in such all-data analyses. Even contradictory results cannot always be excluded and, in a few cases, individual test data had to be omitted. An adequate description of parameters influencing end results should be required.

Table 1—Comparison of Alloy Chemical Composition Between Similar German and AA Designations, %

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	other
AlZn 4.5 Mg1	0.50	0.50	0.10	0.1-0.5	1.0-1.4	0.10-0.25	4.0-4.5	0.01-0.20	0.15
AA7005	0.35	0.40	0.10	0.2-0.7	1.0-1.8	0.06-0.20	4.0-5.0	0.01-0.06	0.15
AA7020	0.35	0.40	0.20	0.05-0.50	0.9-1.5	0.35	3.7-5.0	0.25	0.15
AA7039	0.30	0.40	0.10	0.10-0.40	2.3-3.3	0.15-0.35	3.5-4.5	0.10	0.15

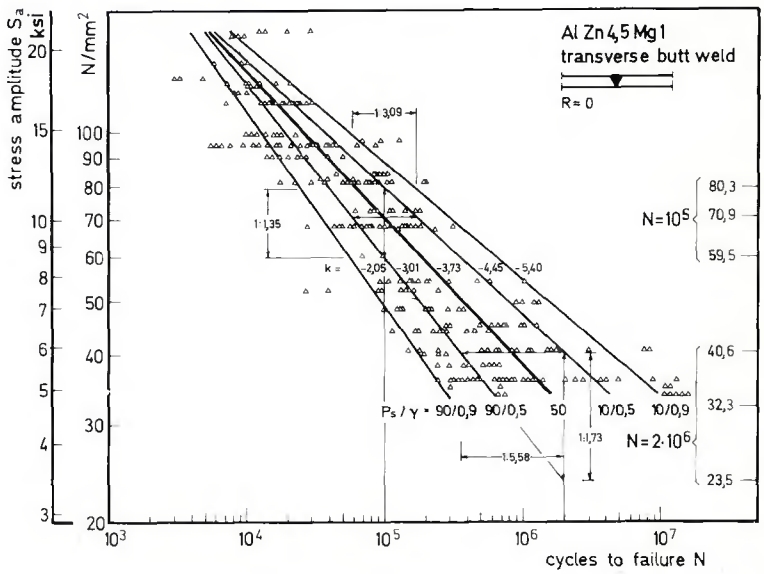


Fig. 4—P-S-N curve

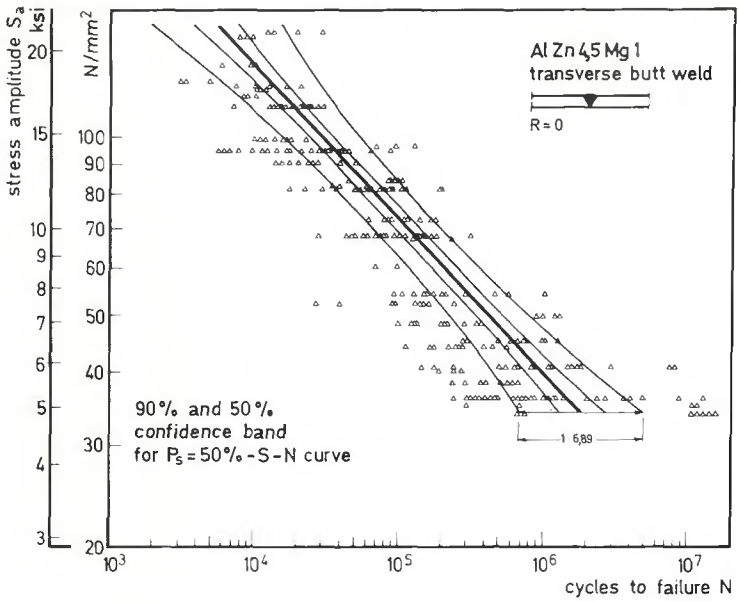


Fig. 5—Confidence limits for best fit curve

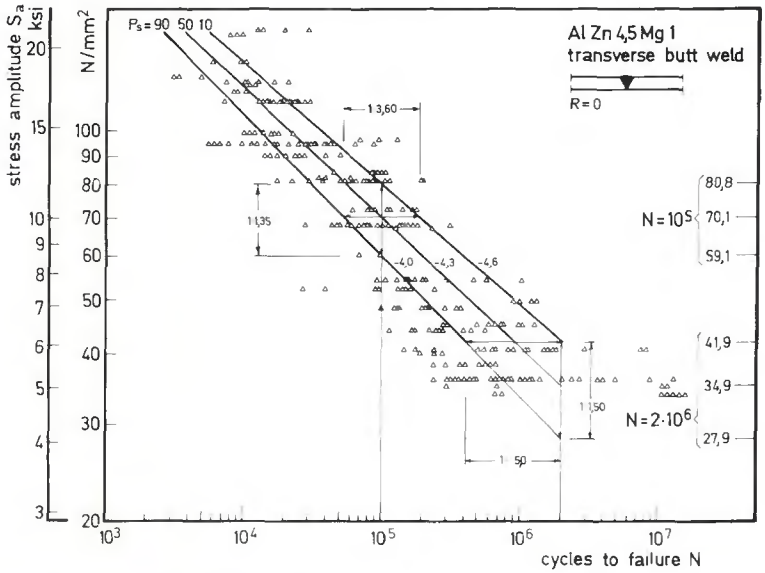


Fig. 6—Normalized P-S-N curve

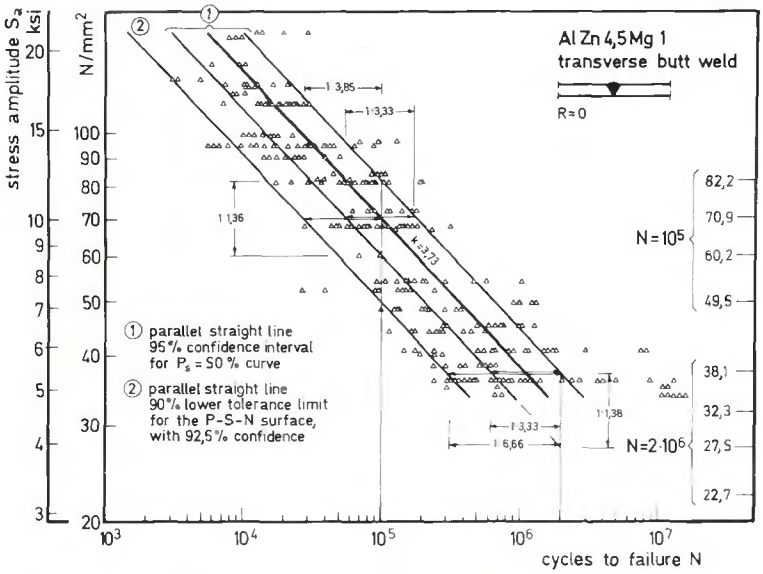


Fig. 7—Single line confidence limits

At this point no clear explanation can be offered for the fact that the fatigue strength of the butt-welded joints in AlZn4,5Mg (7000 series) sinks to a mean level of 32 N/mm² (4.6 ksi) for $2 \cdot 10^6$ cycles compared to the level for butt-welded joints of the 5000 series given[2] at 41 N/mm² (6 ksi), an increase of approximately 30%. This ratio is inversed and falls to about 10% for 10^5 cycles. As is later shown, there appears to be another behavior depending on the R-ratio of AlZnMg-alloys (7000 series) over AlMgMn-alloys (5000 series). Such inconsistencies have to be smoothed out before one attempts a unified approach in codes of practice.

The next obvious step was to assume a certain slope of the S-N-curve and width of the 90% to 10% probability of survival scatter band and then proceed to describe individual test series leading to such a "normalized S-N-curve."[8] An example of this possibility of definition is given in Fig. 6 for an assumed slope of $k = -4.3$ for the mean best fit curve and an assumed ratio of fatigue strength between the 90% and 10% probability curve at $2 \cdot 10^6$ cycles of 1 : 1.5.

Comparing Figs. 6 and 7, one notes the similarities in the scatter band at 10^5 cycles as well as the differences at $2 \cdot 10^6$ cycles due to the naturally much wider computed scatter band at this level. Such a universally accepted normalized curve has the great advantage of uniform description of fatigue behavior of various joint types. One needs to establish only one point (for instance, the fatigue strength at some fatigue life limit), thus fixing the relative position of the S-N-scatter band in log-log coordinates since slope and width of scatter band have been preassumed. Still, on the basis of actual maximum stress responsible for fatigue damage, the relationship between such scatter bands for different weld details or joint types should be computable analytically.

Simplifications such as a universal slope value need to be verified on the basis of actual test results. Still, one is skeptical about the possibility of describing individual test series adequately by means of the normalized curve in its present form and values for the scatter band. Too often, test results do not fall into the scatter band along its whole length; attempting to define broader probability of survival limits would bring back at least some of the

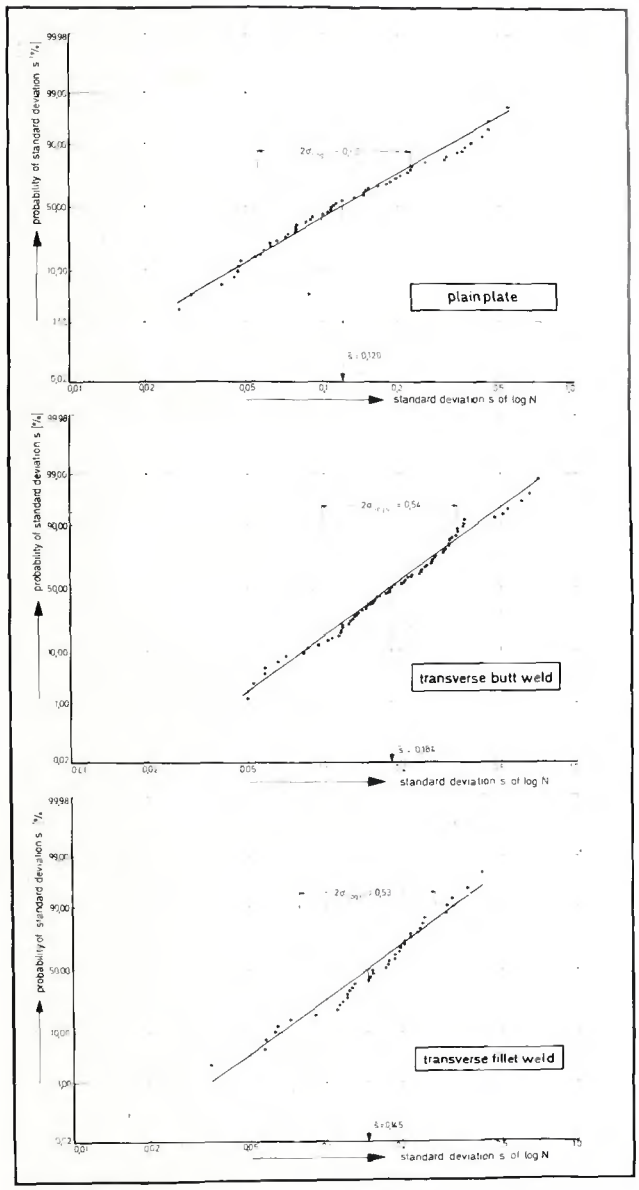


Fig. 8—AlZn$_4$,5Mg1—probability distribution of standard deviation for individual test levels

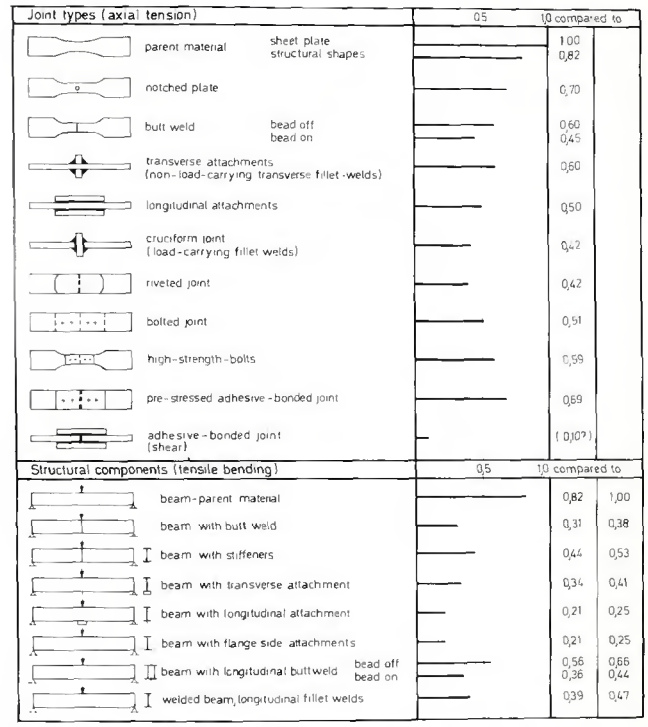


Fig. 9—Fatigue strength of joint and structural components in AlZn$_4$,5Mg1. R = + 0.1/N$_f$ = 2 • 10^6 cycles/mean values

difficulties in the transition point between intermediate fatigue life range with a fatigue life distribution on the one hand and high cycle fatigue range with run-outs and a fatigue strength distribution on the other.

We would like to propose here a modification of the normalized curve concept as a parallel *straight* line lower tolerance limit for the P-S-N surface (Fig. 7). The computation of such limits has been proposed by Little.[9] This scatter band is parallel to the mean curve slope and has the advantage of maximum simplicity. Moreover, first comparisons with results of fatigue strength analyses in the high cycle range seem to indicate a higher level of correspondence, and a smoother transition may be attained. Still, it is felt that further clarification of the statistical concepts used in comparison with the traditional definition of probability of survival limits (taking into account sample size) has to take place before this concept can be recommended.

A closer look at the standard deviation (the main parameter used to express the scatter of fatigue data) is given in Fig. 8. As shown, the probability distribution of the standard deviation of each analyzed stress level (for various notch cases) may be assumed as normal. This clear picture is lost once we try to plot the standard deviation over the mean value of log N for each corresponding stress level. At least for the AlZnMg alloy, no true correlation could be observed. Rather, a cluster of values emerged with only a slight dependency on fatigue life, i.e., higher standard deviation values for higher fatigue life.

Insofar as fatigue data can be analyzed and expressed statistically, a probabilistic design concept can be used. In an early stage of development a design model is conceivable where only one of the quantities is stochastic—for instance, deterministic service loads are compared with stochastic material characteristic values. In any case, probabilistic methods represent a quantitative decision criterion involving the non-physical and non-measurable quantity of structural safety. Experienced engineers have always helped themselves by "intuition" in precarious situations of design and fabrication. In this sense, probability oriented methods will not greatly change fundamental design concepts, but they may offer a more rational and objective rating.

Specimen geometry, test and even material conditions are never truly representative of actual service conditions. Thus, even legitimate statistical inference for simplified tests may be questionable when extrapolated to the structure itself. Figure 9 is an attempt to summarize present knowledge on the fatigue behavior of aluminum alloy structural components. It is a comparative study of the mean fatigue strength for 2 • 10^6 cycles to failure and a stress ratio R = +0.1 of several joint types and structural components in AlZnMg.

This presentation demonstrates how carefully test results on rather simple specimens have to be translated into the expected fatigue behavior of more complex components, whether this

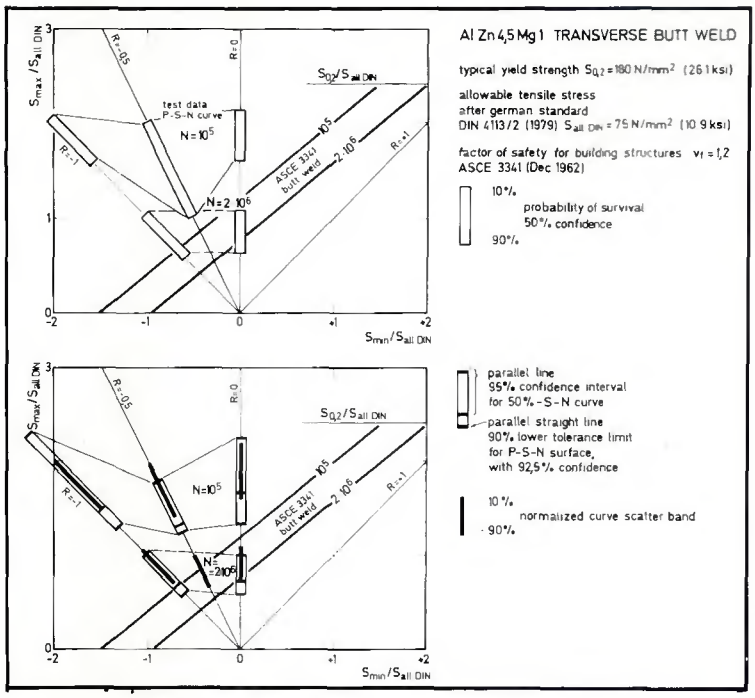


Fig. 10—Constant-life design diagram–transverse butt weld

estimation is done on the basis of actual experimental results or by means of some fatigue life hypothesis. Another point is that available data rarely are so comprehensive as in the case shown. One should also bear in mind the fact that welded joints in real structures may be affected by residual stresses.

Design Standards

Development of welding techniques, the introduction of new alloys and welding electrodes as well as increasing application of these materials in the domain of cranes, bridges and engineering constructions, in general, make it necessary and advisable to study their fatigue behavior more extensively; these also make it necessary to provide for a set of rules to be followed in design and fabrication praxis. The new German standard DIN 4113 (Part 1: general structures and Part 2: welded structures) handles statically loaded structures and does not provide any rules or limits for fatigue behavior in either the intermediate or high cycle range. According to the "Assumptions for Loading and the Safety of Rail Vehicles" by the society, "Leichtbau der Verkehrsfahrzeuge" (light-weight structures for vehicles) design curves for butt welds are given for maximum stress at 10^7 cycles and as a function of the stress ratio.

The problem of fatigue behavior of aluminum weldments is treated by several foreign specifications. The "Suggested Specifications for Structures of Aluminum Alloys 6061-T6 and 6062-T6" ASCE Proc. 3341, Dec. 1962 should be mentioned as one of the pioneer actions in this field. The Belgian code NBN 674 give rules for riveted joints, following the general American provisions. The East German code TGL 21-12500 gives curves of maximum stress over stress ratio and safety factors through which a calculation of allowable stresses is possible. The British code CP 118:1969 "The Structural Use of Aluminum" contains a comprehensive classification of various welded joint types (notch cases) for several cycle values. Also, service loads can be taken into account by means of the linear damage accumulation rule.

Similar provisions are found in the Norwegian code NS 3471 "Prosjektering av aluminium—Konstruksjoner—Beregning of Dimensjonering." This gives maximum stress curves over stress ratio. A "notch factor" is provided, depending on weld or structural detail, stress mode and weld quality. Finally, the Swedish code, "Aluminium-konstruktioner–1966" (the first Scandinavian code) is built in much the same manner and contains comments on fatigue design for service loads as well as for multi-dimensional stress conditions.

A comparative study of the various codes does not produce a uniform

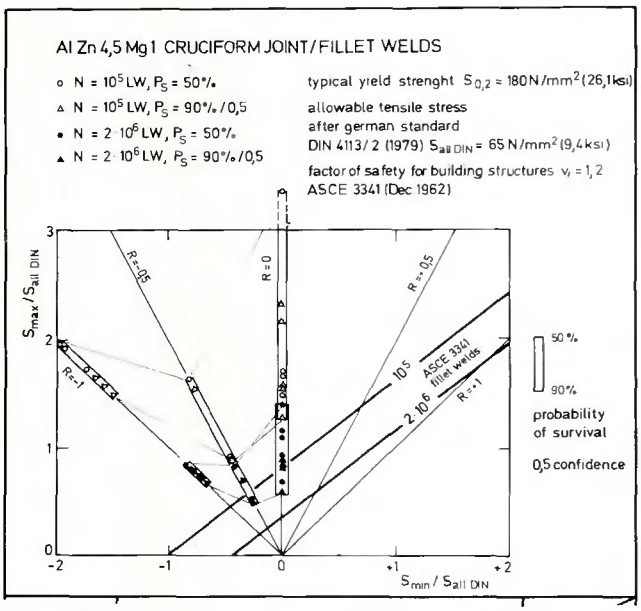


Fig. 11—Constant-life design diagram–cruciform joint/fillet welds

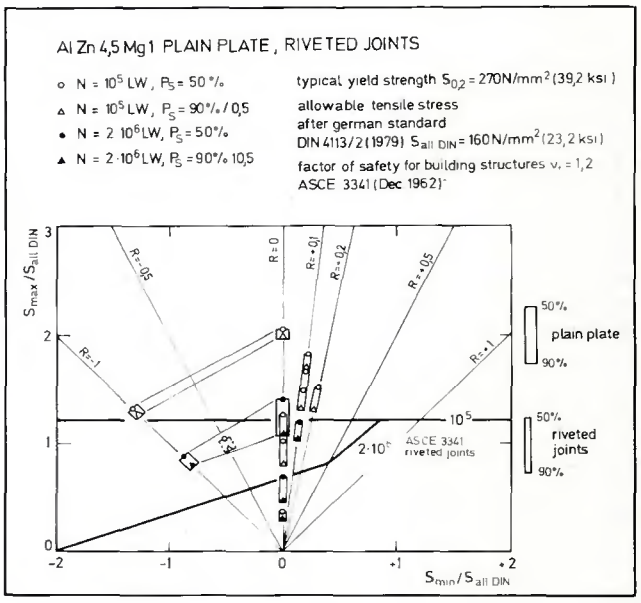


Fig. 12—Plain plate, riveted joints

procedure.[6,13] Different base materials, different weld form or shop practices, welding procedures, varying techniques for the determination of curves of fatigue strength and several definitions of safety factors to estimate allowable stresses, alongside with insufficient experience for the behavior of larger structural components do not allow yet a universal and unified application of these codes. Figures 10-12 are shown as examples of inconsistencies encountered between assumptions in specifications and actual experimental results. Judging especially from the available test results for transverse butt welds in AlZnMg, we have some difficulty in accepting the slope and relative position of dimensioning curves after ASCE 3341.

Guidelines for the Future

Some relevant guidelines which, in the author's opinion, concepts[5,10,11] for a German as well as possibly a European draft of a code of practice for welded aluminum structures under repeated loading will have to follow are as follows:

1. Development of standards for welded aluminum structures will have to be in conformity with the corresponding development of standards of steel structures. Since it has been possible to apply fatigue analysis and evaluation concepts with success in the domain of high strength steels, we feel that an attempt to apply them in welded aluminum structures as well is justified. Simplifying, one could say that aluminum alloys exhibit a similar behavior in fatigue as high-strength steels, only at a lower stress level.

2. Mainly out of economical and time considerations, research will be restricted during this process to absolutely important practical cases and up to the point that a rather reliable description of a parameter influencing fatigue strength or life can be attained.

3. A normalized P-S-N curve of a certain form (linear in log-log coordinates) with a fixed slope and scatter band width for the intermediate fatigue life range, up to a transition life point (eventually variable for different alloy groups) will be assumed. Of course, in a later stage these assumptions will have to be controlled more closely and verified by probability of failure or reliability analyses of real structural components.

4. Aluminum alloys will be pooled in a certain number of groups exhibiting similar fatigue behavior.

5. The traditional approach of grouping welded joint types in certain groups (notch cases) will have to be verified and undertaken on the background of existing and analyzed (as outlined in this paper) data. Opposite to the traditional approach, a grid of fatigue strength values over a "fatigue sensitivity value" (as a representative value integrating the influence of a number of parameters on fatigue strength, with distinct prefixed step differences between single values) will be assumed; the grouping of notch cases will then follow.

6. The possibility that stress range and not maximum stress could be the dominant variable concerning the fatigue behavior of real structure should be examined more closely. The dependence upon mean stress will also be a future research point. There is some evidence, for instance, from experimental results in the USA that, in the case of thicker aluminum weldments, maximum stress and stress ratio are the governing factors rather than stress range and minimum stress.

7. One of the prime unknowns associated with fatigue strength (and this holds especially for civil engineering structures) are service loads. Only scant experimental information exists here. But it is questionable if any progress can be made here quickly.

8. In dealing with environmental influences such as service loads in some form of a spectrum, the linear (Miner) damage accumulation theory will be assumed. Perhaps, for the sake of simplicity, the P-S-N curve will be extropolated with the same slope above the transition point.

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