A statistical analysis of the fatigue behaviour of single and multi-spot welded joints

A. Clifton, H. Nordberg, A. Smith

Several models exist for predicting the fatigue behaviour of a spot welded joint based on geometric data. However, the accuracy of these models tends to diminish as the number of spot welds and complexity of the joint increases. This paper reports on the findings of an investigative study to assess the applicability of a statistical approach to modelling the fatigue behaviour of multi-spot welded joints, based on data obtained from testing single spot welded joints that are geometrically equivalent to the individual welds in the multi-spot joint. A range of fatigue tests were carried out using Staircase and Probit techniques to determine the fatigue strength distribution of a range of multi-spot welded joints, which were subsequently compared to those predicted using the proposed statistical model. The comparison indicated an excellent correlation between predicted and experimentally determined values for standard deviation and a marginal difference for mean fatigue strength values. This difference is potentially attributed to the effects of a degree of load redistribution occurring part way through testing in the multi-spot joints, which is currently not adequately accounted for in the proposed statistical model.

Keywords:
Multi-spot, Welding, Joints, Fatigue, Probit, Staircase, Statistics, Modelling

INTRODUCTION

Multi-spot welded joints are routinely used in the automotive and other industries to produce structurally critical components. Unfortunately, the size and complexity of the joints often limits the practicality of testing their mechanical properties, particularly when long term testing is required such as in the case of determining fatigue properties.

Conversely, single spot welded joints are easily produced and can be tested on existing equipment with little or no modification. Clearly it would be extremely advantageous to be able to predict the fatigue properties of a multi-spot welded component based on the results of a single spot welded joint. This paper will explore the theoretical and practical requirements of determining the fatigue properties of a multi-spot welded joint from the experimental data obtained from fatigue testing single spot welded joints.

STATISTICAL CONSIDERATIONS [1]

The probability of a single spot welded joint surviving beyond a given cycle life at a specific fatigue load, A, will be equal to the probability that the joint has a fatigue strength equal to, or higher than, the given fatigue load A. Since the fatigue strength distribution of a single spot welded joint of a given configuration can be assumed to follow a normal distribution, this probability

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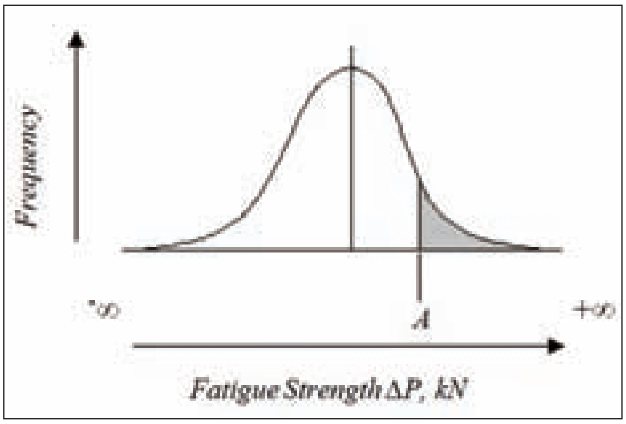

FIG. 1 ***Probability of survival at a given fatigue load.***
Probabilità di resistenza a un certo carico di fatica.

is represented by the integral of the area under the distribution curve between the specified load, A, and +∞. This is equivalent to the difference between the total area under the curve and the cumulated area up to load A.

If the failure of a multi-spot welded joint is defined as failure of at lest one of the weld nuggets, then the probability of survival for the entire multi-spot weld joint will be equal to the product of the survival probabilities of each of the individual spot welds at the specified load.

If it is assumed that all welds have equal properties and the load is evenly distributed, such that each spot weld is supporting an equal share of the overall load at all times, then the individual survival probability of each spot weld will be identical. The use of these boundary conditions leads to a simplified model that suggests that the probability of a multi-spot welded joint surviving a fatigue test, with a specific load applied to each individual weld nugget, will be equal to the probability of survival for a single spot welded joint supporting the same load to the power of n, where n is the number of weld nuggets present in the joint.

$P(MS) = P(SS)^n$ Equation (1)

Where:

P(MS): Probability of survival for a multi-spot weld joint
P(SS): Probability of survival of a single spot weld joint
n: Number of weld nuggets that make up the multi-spot weld joint

If it is assumed that, for a cycle life of 10^6 cycles, the mean fatigue strength of a single spot welded joint (which is the load that will give a 50% chance of survival) is X, and the probability distribution has a standard deviation of S, the various values of fatigue load can then be generalised as the mean strength, X, plus or minus some fraction, K, of the standard deviation, S.

$X \pm K \times S$ Equation (2)

If, for convenience, the probability of a joint surviving at any given fatigue load is denoted as the total area under the distribution curve, 1, minus a function of the fatigue load, then the probability of a joint surviving the 10^6 cycles at any fatigue load can be generalised as:

$1 - f(X + K \times S)$ Equation (3)

Where:

1: The total area under the distribution curve
X: The mean fatigue load for a single spot weld joint
K: Any real number
S: The standard deviation of the distribution for a single spot weld joint
f(X + K × S): Probability of failure for the load X + K × S, which, as discussed, can represent any fatigue load

Similarly, the survival probability of a multi-spot welded joint tested under the same conditions, except with the same fatigue load applied to each individual weld nugget, can be represented as:

$[1 - f(X + K \times S)]^n$ Equation (4)

Where:

1-f(X + K × S): The probability of survival for a single spot weld joint at an applied load of X + K × S
n: The number of weld nuggets present in the multi-spot weld joint.

As X and S are constants, values for the survival probability for various multi-spot weld joints can be determined for various values of K, since K corresponds directly to the Z values used in standard normal distribution tables.
From the plotted survival probabilities, the mean fatigue strength and standard deviation per nugget of any multi-spot welded joint can be related to the mean fatigue strength and standard deviation of a single spot welded joint in terms of X + K × S by a specific value of K, which for convenience will be denoted m_n and d_n for mean fatigue strength and standard deviation respectively. For example, the mean fatigue strength per nugget for a sixteen nugget joint can be related to the mean fatigue strength and standard deviation of a single spot welded joint as:

k	n = 1	n = 2	n = 4	n = 8	n = 16
0.0	0.500	0.250	0.063	0.004	0.000
-0.5	0.692	0.478	0.229	0.052	0.003
-1.0	0.864	0.747	0.558	0.311	0.097
-1.5	0.933	0.871	0.758	0.575	0.331
-2.0	0.977	0.955	0.912	0.832	0.691
-2.5	0.995	0.991	0.981	0.963	0.927
-3.0	0.999	0.997	0.995	0.990	0.979

TABLE 1 ***Survival probabilities for various values of n at various values of K.***

Probabilità di resistenza per diversi valori di n a diversi valori di K.

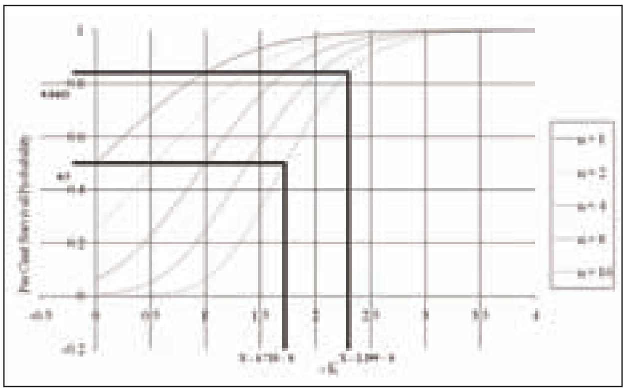

FIG. 2 ***Survival probabilities for 1 to 16 nugget joints at loads in terms of X+ K × S.***

Probabilità di resistenza per giunti aventi da 1 a 16 punti di saldatura ai carichi in termini di X+ K × S.

$X - 1.723 \times S$ Equation (5)

Therefore $m_n = 1.723$

Similarly, the standard deviation per nugget for a sixteen nugget joint can be related to the mean fatigue strength and standard deviation of a single spot welded joint as:

$(X - 2.299 \times S) - (X - 1.723 \times S) = 0.576 \times S$ Equation (6)

Therefore $d_n = 0.576$

Plotting the values of m_n and d_n for increasing values of n produces a graphical representation of how mean fatigue strength and standard deviation per nugget changes as the number of weld nuggets in the joint increases. Based on these assumptions, it should be possible to predict the fatigue properties of a multi-spot welded joint from the experimental data obtained from fatigue testing single spot welded joints.

Boundary Conditions
In order to determine if support for the proposed theory is justified, certain assumptions and boundary conditions need to be

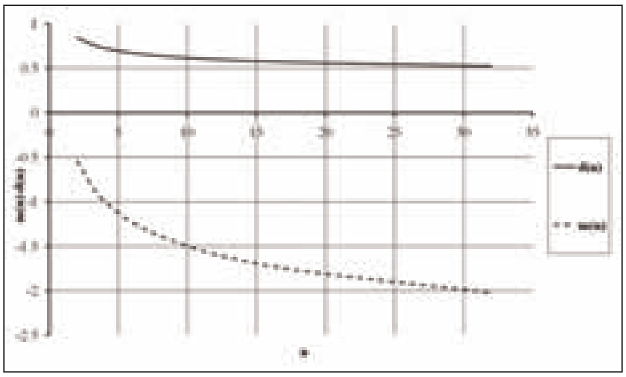

FIG. 3 ***Changes in mn and dn for joints with various numbers of nuggets (n).***

Variazioni in mn e dn per giunti con diversi numeri di punti di saldatura (n).

established to control as many of the parameters as possible. Below is a summary of the necessary assumptions and conditions.

Equal Loading

Each individual nugget must support an identical proportion of the overall load throughout the test. If this condition is not fulfilled then the survival probability of each nugget will lie at a different point on the distribution curve and will therefore have a different value. To maintain a balanced load, simple Tensile Shear Spot Welded (TSSW) joints were used with welds made in a straight line across the centre of the overlap. The joints were then loaded in shear using jaws wide enough to support their entire width. Shim plates, equal in thickness to the sheets to be joined, were applied outside the free length of the specimens to maintain the eccentric loading regime associated with lap joints.

Equal Weld Properties

Without equal weld properties the failure distribution will vary for each individual nugget, resulting in a different probability of survival for each nugget at a given load. To ensure equal weld properties, a weldability study was carried out using various magnitudes of welding time, welding current and electrode force, but maintaining all other parameters at a constant value. The properties and repeatability of the nuggets produced at each set of different welding parameters were then measured using lap shear tests and by microscopic evaluation of nugget diameter. An AC spot welder was also used to reduce the potential of heat imbalances caused by the flow of current in a single direction.

The following parameter levels were found to produce welds with an optimum balance of weld nugget strength and consistency of properties:

Welding Time: 15 Cycles (50 Hz supply)
Welding Current: 4.5 kAmps
Electrode Force: 3.25 kN
Resulting Average Weld Nugget Diameter: 4.3 mm

In addition, the effect of leak current on the uniformity of the nuggets made in the multi-spot weld specimens was minimised through an examination of the weld diameter and tensile-shear mechanical strength of welds made at various pitch distances. An optimum pitch distance of 20 mm was found to produce dimensionally and mechanically consistent welds, whilst maintaining manageable specimen sizes.

Joint Geometry

Studies have shown that for high cycle fatigue (>10^4 cycles), the fatigue properties of as-welded TSSW joints are dependent on the joint geometry and not on the strength of the base material [2] [3] [4] [5]. The reasoning for this dependence on joint geometry is believed to be due to the effect that various dimensions have on the resistance of the joint to rotate, which is the primary mechanism for crack propagation in TSSW joints, and thus their effect on prolonging fatigue life [3] [4] [6] [7]. The resistance a given joint has to rotation is often referred to as 'joint stiffness', which is defined as the amount of joint rotation per unit of fatigue load. Various investigations have been carried out to measure the effect that a variety of geometric parameters have on fatigue life, and although the effects vary, the very fact that joint geometry affects fatigue properties means that, in this study, it needs to be controlled and kept constant. Dimensions for free length and overlap of 100 mm and 40 mm respectively were chosen based on previous work on fatigue testing multi-spot welded joints by Jan Linder [9] [10] [11]. These dimensions were kept constant for all single and multi-spot weld specimens. The thickness of the sheets to be joined was kept constant at 1 mm for all single and multi-spot joints. The optimum pitch distance of 20 mm was used primarily as the separating distance between individual spot welds on all multi-spot welded joints. However, due to the need for consistency between single and multi-spot welded joints, the optimum pitch distance was also used as the width of the single spot weld specimen and as the basis for the edge distance on all specimens (edge distance was equal to 0.5 pitch distance). This meant that single spot welded joints would be geometrically identical to individual spot welds in the multi-spot welded specimens.

Failure

Since the criterion for survival of a multi-spot joint has been defined as the survival of 100% of the present welds, the instant that one weld meets the conditions for failure, the whole joint is also deemed to have failed. To maintain consistency in the tests, what constitutes the failure of a single spot welded joint must also constitute the failure of an individual spot weld in a multi-spot weld joint.

The fatigue crack life of a TSSW joint can be generalised into 3 stages of growth, crack initiation, through thickness crack growth, and lateral crack growth. Crack initiation is generally thought to account for a very small portion of the fatigue life of TSSW joints [2] [4] [6] [7] [8]. This is due to the existence of a sharp, crack like notch at the edge of the weld fusion zone, ai-

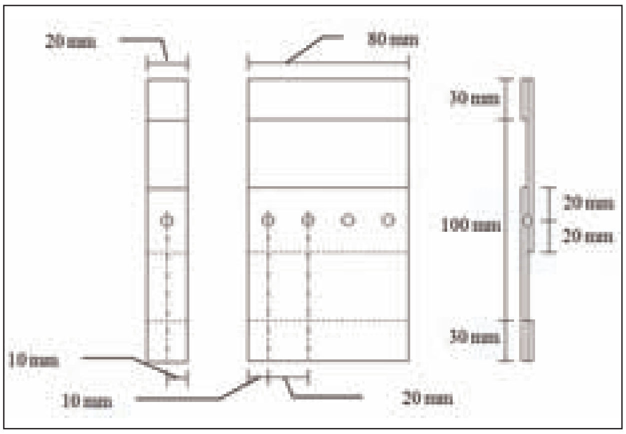

FIG. 4 ***Geometry of test specimens.***

Geometria dei provini.

ding initiation [6] [7] [8]. The through thickness cracking begins at this crack like notch and propagates at an angle of approximately 80o to the loading direction, through the thickness of the plate [2] [6] [7] [9] [10]. Once on the surface, the crack grows laterally across the specimen width [7] [8] [11].
Industry generally prefers a conservative definition of fatigue failure in TSSW joints by defining it as the point where the crack has penetrated the external surface [12]. However, this approach is difficult to categorise whilst testing, especially when considering multi-spot welded joints. Instead, for the purposes of the tests carried out in this study, the failure of an individual spot weld was defined as the point at which the spot weld nugget could no longer support load. This corresponded to a large surface crack, which, in the case of these specimens, spans a distance approximately equal to 0.5 pitch distances either side of a weld nugget. To monitor when this condition had been met, a combination of jaw displacement and time lapse video monitoring was used.

Normal Distribution
The assumption that the fatigue failure distribution for single and multi-spot welded joints fits a normal distribution can be made, provided all the afore mentioned conditions are adhered to.

EXPERIMENTAL PROCEDURE
To generate evidence to support the proposed theory, a specific route of fatigue testing was followed. All fatigue tests were carried out in "load control" using identical testing parameters (stress ratio of 0.1 and a cycle life of 10^6 cycles) and maintaining constant testing conditions.

Staircase Testing Single Spot Welded Joints
Initial values for the mean fatigue strength and standard deviation for the fatigue strength distribution of single spot welded joints were determined using a Staircase fatigue testing process. The testing procedure and analysis of results were carried out in accordance with documented methods [13], [14], [15], [16], [17].

Probit Testing Single Spot Welded Joints
The initial values of mean fatigue strength and standard deviation, derived from the Staircase tests, were used to construct an estimate of the distribution of failure probability for increasing fatigue loads for single spot welded joints. From this estimated distribution, load levels were determined that would theoretically produce per cent survival probabilities of 10%, 30%, 50%, 70% and 90%. Fatigue tests were then carried out at these load levels using weighted group sizes as described in documents methods for Probit testing [13], [18]. The actual per cent survival probability of single spot welded joints at these load levels was then plotted and a response curve was fitted to the data using the defined Probit assessment procedures [13]. This gave an accurate representation of the complete distribution of failure probability for increasing fatigue loads of single spot welded joints.

Staircase Testing Multi-Spot Welded Joints
The values for mean fatigue strength and standard deviation taken from the Probit data for single spot welded joints were used in accordance with the proposed theory to generate estimate values for mean fatigue strength and standard deviation per nugget for joints consisting of two, four, eight and sixteen nuggets.
A Staircase test process was then carried out on each of these joint configurations to determine empirical values for the mean fatigue strength and standard deviation per nugget for joints consisting of two, four, eight and sixteen nuggets. As with the single spot weld joint Staircase study, the process and analysis of results were carried out in accordance with documented methods [13], [14], [15], [16], [17].

Comparison of Empirical Multi-Spot Data and Theoretical Data
The empirical results for mean fatigue strength and standard deviation per nugget obtained from the Staircase study of two, four, eight and sixteen nugget joints was then compared to the theoretical values determined using the single weld Probit data combined with the proposed theory.

RESULTS
Single Nugget Staircase Results

Load Range, kN	Step No. i	Test Number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Number of Survivals, r	Number of Failures, f
0.729								X																			0	1
0.702	2		X		X		O		X						X		X				X						1	6
0.675	1	O		O		O				X		X		O		O		X		O		X		X		X	6	6
0.648	0										O		O						O				O		O		5	0
																											Σr	Σf
																											12	13

Calculated values based on Survivals as the Least Frequent Event (LFE):
Mean load: 0.680 ± 0.008 (95% Conf.) Standard Deviation (SD): 0.018 ± 0.009

TABLE 2 ***Staircase results for single nugget fatigue tests.***
Risultati della prova Staircase per le prove a fatica dei singoli punti di saldatura.

Single Nugget Probit Results

Applied Load, kN			Results		
ΔP	P_{max}	P_{min}	No. Tested	No. Surviving	Actual % Survivng
0.639	0.71	0.071	40	37	92.50
0.657	0.73	0.073	20	9	45.00
0.666	0.74	0.074	20	9	45.00
0.675	0.75	0.075	20	9	45.00
0.684	0.76	0.076	30	4	13.33

TABLE 3 ***Probit results for single nugget fatigue tests.***

Risultati della prova Probit per le prove a fatica dei singoli punti di saldatura.

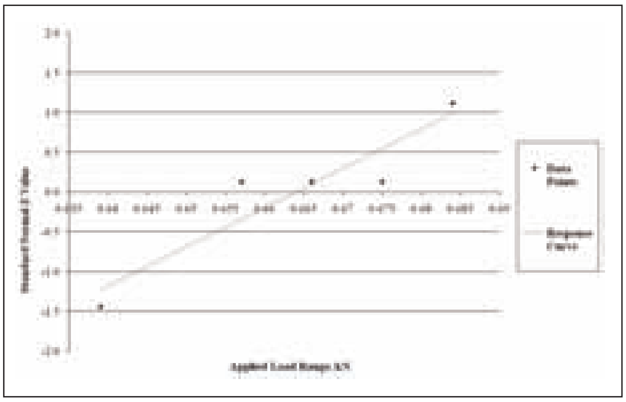

FIG. 5 ***Probit plot for single nugget fatigue tests.***

Tracciato Probit per le prove a fatica dei singoli punti di saldatura.

Double Nugget Staircase Results

Load Range, kN	Step No. i	Test Number																														Number of	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Survivals, r	Failures, f
1.413	2				X		X																		X		X					0	4
1.377	1			O		O		X		X				X		X						X		O		O		X		X		4	7
1.341	0		O						O		X		O		O		X		X		O		O						O		X	7	4
1.305		O										O						O		O												4	0
																																Σr	Σf
																																15	15

Calculated values based on Failures as LFE:
Mean/weld nugget: 0.680 ± 0.006 kN (95%Conf.) SD: 0.016 ± 0.008 kN (95%Conf.)

TABLE 4 ***Staircase results for double nugget fatigue tests.***

Risultati Staircase per le prove di fatica sui doppi punti di saldatura.

Four Nugget Staircase Results

Load Range, kN	Step No. i	Test Number																														Number of	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Survivals, r	Failures, f
2.952	3																			X				X								0	2
2.898	2										X		X						O		X		O		X				X			2	5
2.844	1			X		X		X		O		O		X		X		O				O				X		O		X		5	7
2.79	0		O		O		O		O						O		O										O				X	7	1
2.736		O																														1	0
																																Σr	Σf
																																15	15

Calculated values based on Failures as LFE:
Mean/weld nugget: 0.712 ± 0.005 kN (95%Conf.) SD: 0.015 ± 0.008 kN (95%Conf.)

TABLE 5 ***Staircase results for four nugget fatigue tests.***

Risultati Staircase per le prove di fatica su quattro punti di saldatura.

Eight Nugget Staircase Results

Load Range, kN	Step No. i	Test Number																														Number of	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Survivals, r	Failures, f
5.679	2						X				X																					0	2
5.58	1					O		X		O		X				X				X				X		X		X		X		2	8
5.481	0		X		O				O				X		O		X		O		X		O		O		O		O		X	8	5
5.382		O		O										O				O				O										5	0
																																?r	?f
																																15	15

Calculated values based on Failures as LFE:
Mean/weld nugget: 0.689 ± 0.003 kN (95%Conf.) SD: 0.009 ± 0.004 kN (95%Conf.)

TABLE 6 ***Staircase results for eight nugget fatigue tests.***

Risultati Staircase per le prove di fatica su sei punti di saldatura.

Sixteen Nugget Staircase Results

Load Range, kN	Step No. i	Test Number																														Number of	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Survivals, r	Failures, f
11.39	2																										x				x	0	2
11.2	1			x				x		x						x		x				x				o		x		o		2	7
11.01	0		o		x		o		o		x		x		o		o		x		o		x		o				o			8	5
10.82		o				o						o		o						o				o								6	0
																																?r	?f
																																16	14

Calculated values based on Failures as LFE:
Mean/weld nugget: 0.619 ± 0.004 kN (95%Conf.) SD: 0.009 ± 0.004 kN (95%Conf.)

TABLE 7 ***Staircase results for sixteen nugget fatigue tests.***

Risultati Staircase per le prove di fatica su sedici punti di saldatura.

Correlation Between Theoretical Values and Empirical Values

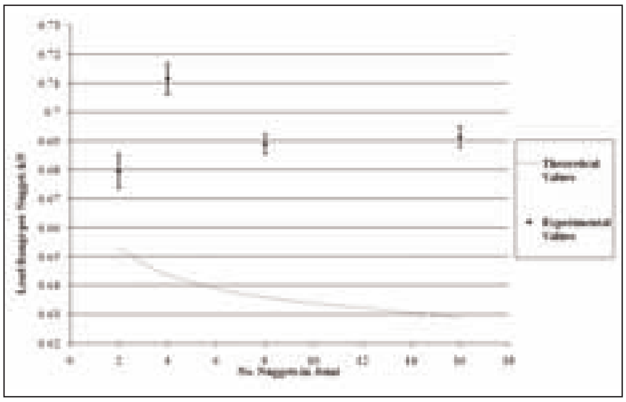

FIG. 6 ***Mean fatigue strength per nugget: theoretical vs. empirical.***

Resistenza a fatica media per punto di saldatura: teorica vs. empirica

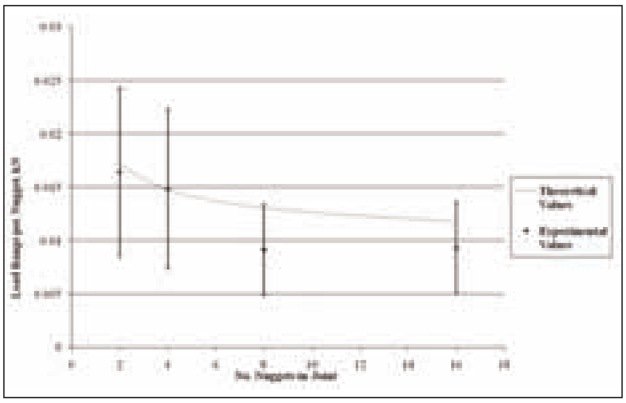

FIG. 7 ***Standard deviation per nugget: theoretical vs. empirical.***

Deviazione standard per punto di saldatura: teorica vs. empirica.

DISCUSSION

Single Nugget Fatigue Tests

The response curve fitted to the Probit data points correlates well with the estimated Probability Density Function (PDF) that can be produced from the Staircase data. The main inconsistency between the two plots is in the positioning of the mean fatigue strength value, which can be found at the point where the plotted data lines cross the x-axis.

The similarities between the gradients of the two lines indicate that the values for the individual standard deviations, displayed by the two distributions, vary very little from one another. This is confirmed in the results, which show standard deviations of 0.0183 kN and 0.0203 kN for the Staircase and Probit results respectively.

This is reassuring, since it removes a considerably amount of doubt in the ability of the Staircase testing process to produce reliable values for standard deviation. This would suggest that the standard deviation values for the multi-spot welded joints generated by the Staircase process will be comparable in accuracy to those that could be generated using the more time consuming, but generally more accurate, Probit process.

By indicating such a small standard deviation, these results suggest that the capability of the specimen production process and equipment to produce welds with consistent fatigue properties was significantly underestimated. However, it means that even very minor changes in the applied load range could result in significant changes in the probability of survival. Therefore, if the equipment is not able to accurately produce the loads requested of it, it could cause a significant change in the outcome of the test.

The minor discrepancy between the mean fatigue strength values calculated by the Staircase and Probit distributions is a case in point. If the individual data points plotted from the Probit results are considered, it can be seen that there is a degree of ambiguity around the mean level, with three different load levels each purporting to produce a 45% probability of survival. As explained, these inaccuracies could be a consequence of having such a small standard deviation, since small standard deviations mean that if the equipment deviates, even slightly from the requested load, there will be a significant difference between the predicted and actual survival probability. It is therefore likely that since these three load levels were so close to one another, the equipment had trouble accurately and consistently producing the individually requested loads for the three data points without some degree of overlap. This resulted in the survival probability of the three data points being equal.

Since the Probit study was carried out using a significantly larger sample size, the value it calculates as being the mean fatigue strength will be a more accurate representation of the actual value when compared to the one predicted by the Staircase process, it was therefore chosen to predict the values required to Staircase test the multi-spot welded joints. Fortunately, the problem explained above does not indicate that the values predicted by the Staircase process for the multi-spot welded joints will be inaccurate. This is because the load range levels used in the multi-spot welded tests are larger and more spread out. This makes it much easier for the fatigue equipment to accurately and consistently produce the required load levels.

Multi-Spot Weld Staircase Tests

For each of the different multi-spot welded specimen configurations tested, it was clear early on that the values for the mean fatigue strength, predicted by the proposed theory and the collected Probit data, would be lower than the ones determined experimentally, since the first group of results from each multi-spot welded joint configuration tested were all survivals. These early results were omitted from the results and analysis stages, since they did not form part of the active levels.

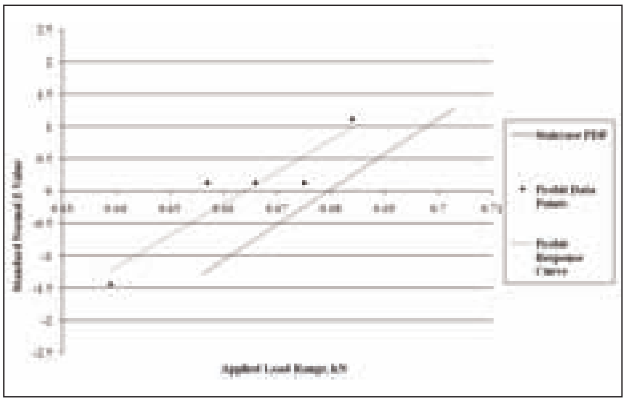

FIG. 8 ***Comparison of Staircase PDF and Probit response curve for single nugget joints.***

Confronto fra PDF Staircase e curva della risposta Probit per giunti a singolo punto di saldatura.

Once the first turnaround point had been found, and data for the active levels was being collected, it became apparent that the predicted values for standard deviation were reasonably accurate, as the spread of active load levels was at an acceptable level.

Correlation Between Theoretical and Empirical Mean Fatigue Strength Data

The experimental results for mean fatigue strength per nugget all appear to be higher than the proposed theoretical values, in particular for the four nugget specimens. The difference between the corresponding theoretically proposed values and experimental values is small in terms of an absolute scale, however, in terms of the distributions that they represent, they are all at least 5 standard deviations higher than expected. This would suggest that the correlation between the estimated magnitudes and the actual magnitudes is very poor.

For the most part, the general trend shown by the experimental results does follow the theoretical trend. This could indicate that the theoretical changes in mean fatigue strength are consistent with actual values, but that the inclusion of more that one nugget in the joint 'steps' up the magnitudes of the mean fatigue strength per nugget by a certain amount.

The cause of this raise in magnitude between the proposed theoretical values and the experimentally determined ones could be caused by load redistribution. With the single nugget specimens there is only the behaviour and effect of a single fatigue crack to consider, whereas with the multi-spot welded specimens, there are many fatigue cracks occurring simultaneously. When one of these fatigue cracks reaches a certain size it could cause a reduction in the specimen stiffness in the immediate vicinity of the spot weld adjacent to the fatigue crack, which would result in a reduction in the proportion of the overall load supported by this spot weld. The surplus load resulting from the decreased support from this spot weld would then be taken up by the two adjacent spot welds causing a redistribution of load and therefore stress. This reduction in supported load at the initial crack site would result in a reduction in the cracks growth rate, while the increase in supported load by the two adjacent spot welds would cause an increase in the growth rate of the fatigue cracks in the vicinity of these two welds.

Since load redistribution can not occur in single spot welded joints the fatigue crack grows at a fairly constant rate, without needing to stop and start as other cracks take and yield dominance, therefore in single nugget joints the choice of a failure criteria based on crack length is inconsequential. Applying the same condition to a multi-spot welded joint however raises issues if the failure crack length is above the length at which load redistribution occurs, since it means the loading conditions per spot will not be equal throughout the test, which is a critical boundary condition of the proposed theory. If this was the case, the ultimate affect of load distribution would be to increase the fatigue life of a multi-spot welded joint at a given load range when compared to a multi-spot welded joint tested at the same load range that does not experience load redistribution. This would result in the whole distribution shifting up on the load scale, meaning a higher mean fatigue strength per spot than predicted, which is what has been observed here.

Correlation Between Theoretical and Experimental Standard Deviation Data

The correlation between the experimental and theoretically proposed results for the standard deviation per nugget is very good. The slight variation between the experimental results and theoretical values for the standard deviation per nugget on the eight nugget specimens could be due to insufficient accuracy in the application and recording of the fatigue loads. Since the values are very small, even minor errors would result in apparently large deviation from the predicted values.
The correlation between the experimental and theoretical results for standard deviation indicate that, whatever the cause for the variation between the theoretical and experimental mean fatigue strength results, it is consistent for a given specimen configuration. The correlation gives support to the proposed theory and indicates that the relationship for mean fatigue strength should work once the cause of the observed increase in the magnitude of the mean fatigue strength is taken into consideration.

CONCLUSIONS

- The fatigue failure behaviour of single spot welded joints of this size and configuration is consistent with that which has been published in the past.
- The results for the theoretical values for mean fatigue strength per spot do not appear to match those obtained through experimentation, although the general trend of changes in value as the number of nuggets present in the joint increases, appears, for the most part, to have good correlation.
- The results for the theoretical values for standard deviation appear to correlate well with those obtained through experimentation.
- This partial correlation would suggest that the presented theory is close to being accurate, but there is evidently a factor remaining which increases the position of the individual failure distributions for multi-spot specimens on the load scale.

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Abstract

Analisi statistica del comportamento a fatica di giunti saldati mediante saldatura a punti singoli e multipli

Parole chiave: saldatura – fatica – modellazione

Esistono diversi modelli per prevedere il comportamento a fatica di un giunto saldato mediante saldatura a punti sulla base dei dati geometrici. Tuttavia, la precisione di questi modelli tende a diminuire con l'aumentare del numero dei punti di saldatura e del grado di complessità dei giunti. Questo studio riporta i risultati di un' indagine effettuata al fine di valutare l'applicabilità di un approccio statistico per la modellazione del comportamento a fatica di giunti saldati mediante saldatura a punti multipli, in base ai dati ottenuti in prove su giunti saldati a punti singoli che sono geometricamente equivalenti a saldature individuali nel giunto saldato mediante saldatura a punti multipli. Sono state condotte una serie di prove di fatica utilizzando tecniche Staircase e Probit per determinare la distribuzione della resistenza alla fatica di una serie di giunti saldati mediante saldatura a punti multipli, che sono stati successivamente confrontati con quelli previsti utilizzando il modello statistico proposto. Il confronto ha fatto emergere una eccellente correlazione tra i valori previsti e quelli determinati in via sperimentale in termini di deviazione standard e una differenza marginale per valori medi di resistenza a fatica. Questa differenza è potenzialmente attribuibile agli effetti di un certo grado di ridistribuzione del carico che si verifica in un punto intermedio delle prove nei giunti saldati mediante saldatura a punti multipli, che attualmente non è adeguatamente rappresentata nel modello statistico proposto.