Optimisation of weld size in single-sided groove butt joint

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Abstract - *The welding parameters influence the static strength of the butt weld joint used in the mechanical structures. It is essential to make correct-size welds, as an oversized weld is very costly and may not have good strength. It wastes welding consumables and may cause other fabrication problems, including excessive distortion. This study aims to use an appropriate optimisation method and finite element analysis model to develop a mathematical model to predict the required weld size. The results show that half-fraction factorial design is an appropriate optimisation method. The increase in applied load and safety factor leads to an increase in the required weld size. The lower tensile strength electrode leads to a bigger weld size. The developed mathematical model predicted the size of weld needed for a single-sided groove butt joint for the range of the used parameters.*

Key Words: butt weld, optimisation, finite element analysis, weld size, single-sided groove butt joint

1. INTRODUCTION

A butt joint is the most accessible welding joint to perform (next to the fillet weld). It is high strength with complete fusion and somewhat less susceptible to contamination. It is easy to inspect for distortion, easy to machine after welding and applicable to a variety of metals. It is excellent for continuous linear or circumferential welds. Filler material strength, base material strength, and weld geometries, such as weld size, are essential factors in evaluating static strength [1]. The study [3] developed an appropriate method for predicting the ultimate tensile strength of partially penetrated groove welds and proposed design equations. The study [4] developed expressions for predicting the ultimate load and deformation capacities in the fillet welds. The study [5] shows that a finite element analysis (FEA) model could be developed whose estimations for load carrying capacity of butt-welded joints agree with the experiment results. The above studies indicate that the requirement of the weld size in single-sided groove butt weld may vary with different combinations of applied load, the factor of safety and electrode material strength.

Therefore, this study's main aim is 1) To select an appropriate optimisation method to refine the weld size; 2) To use FEA model to find the effect of applied tensile load on the weld size; 3) To use FEA model to find the effect of factor of safety on the weld size; 4) To use FEA model to find the effect of electrode tensile strength on the weld size 5) To develop a mathematical model to predict the required weld size. This study aims to contribute to an understanding of using an appropriate optimisation method to enhance the weld size. In addition, it will help in understanding the effect of applied load, safety factor and electrode tensile strength on the single-sided butt joint weld size.

2 STATIC JOINT DESIGN

To satisfy the welding criteria [1], alloy steel is selected as the base material of the plates to be butt welded. The base material has a minimum yield strength of 620 MPa (< 690 MPa) and a base material plate thickness of 6 mm (>3mm). Electrode filler material strength mismatch m in welds is the ratio of filler material yield strength to the base material's yield strength. Based on this ratio, if m < 1, the case is called under-matching [2]. The study [5] recommended a mismatch ratio of m <= 0.7 for the testing of the butt weld joints. Therefore, in this study, electrodes E60 and E70 are selected as the electrode filler material yield strengths are 458.5 MPa and 479.9 MPa, respectively. As a result, the mismatch ratio is 0.7 and 0.77, respectively.

2.1 Specimen geometry

A specimen of alloy steel material with dimensions of 400 mm x 37 mm x 6 mm, as shown in Fig. 1, was used for FEA. The FEA model was built as an assembly using mate constraints on two plates of size 200 mm x 37 mm x 6 mm. An alloy steel has a yield strength of 620 MPa and an ultimate tensile strength of 723.8 MPa.

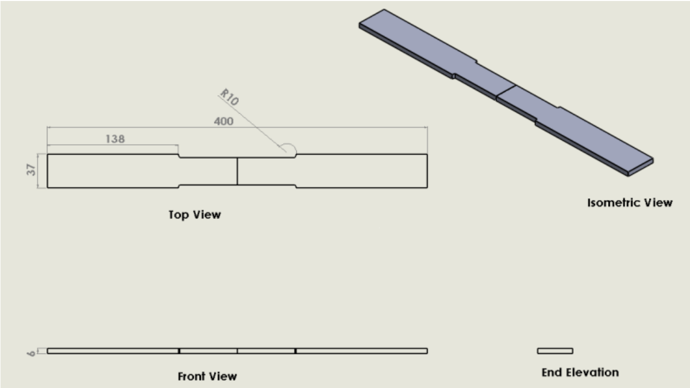

Fig -1: Dimensioned drawing of the specimen

2.2 Equipment

The study used SolidWorks CAM, Microsoft Excel, and Minitab 2023 software.

2.3 Specimen Preparation

The specimen part file was created as per the study [5] using SolidWorks 2023 software.

2.4 Welding

The default software setting of the single-sided groove butt joint was applied to both half plates of the specimen to form a butt joint.

3. DESIGN PARAMETERS

3.1 Parameters, Levels and Responses

Table 1 shows the level settings of the welding parameters, such as load, safety factor, electrode and weld size. The required weld size was selected as the response. The range of welding operation parameters was chosen as per the American welding code [1], and initial FEA trial runs were performed using SolidWorks software.

TABLE-1: LEVEL SETTINGS OF LOAD, SAFETY FACTOR, ELECTRODE AND WELD SIZE FOR REQUIRED WELD SIZE AS RESPONSE VARIABLE

Serial No.	Input variables level settings		
	Input variables	***Low level***	***High level***
1	Load (N)	7500	30000
2	Safety Factor	1	5
3	Electrode	E60	E70
4	Weld Size (mm)	3	12.7

To determine whether there is a linear or non-linear relationship between the load, safety factor, electrode, weld size and the required weld size, a null hypothesis (H_0) is that there is a linear relationship between the input and response variables. An alternative hypothesis (H_1) is that there is no linear relationship between the input and output variables. As a result, a half-fraction factorial design is used.

3.2 Half-Fraction Factorial Design

The study used Minitab 2023 software to create a randomised run order for the experiment involving four process parameters with low-level and high-level settings of the input variables load, safety factor, electrode and weld size, as shown in Table 2. The half-fraction factorial design consists of eight factorial points and two center points or ten points (Run 1-10). The half-fraction factorial design is shown in Table 2.

The experimental runs were performed on the SolidWorks software. The study used the default settings of the single-sided groove weld joint of SolidWorks software. The load, safety factor, electrode, and weld size values were changed as per Table 2, and the required weld size was recorded (as shown in Table 2) for each experiment.

TABLE-2: LEVEL SETTINGS OF LOAD. SAFETY FACTOR, ELECTRODE AND WELD SIZE FOR REQUIRED WELD SIZE AS RESPONSE VARIABLE

Run Order	**Load (N)**	**Safety factor**	**Electrode**	**Weld size (mm)**	**Required weld size (mm)**	**Success**
1	30000	1	E70	3	3.16	Fail (0)
2	7500	1	E60	3	0.92	Pass (1)
3	30000	5	E70	12.7	15.82	Fail (0)
4	30000	1	E60	12.7	3.69	Pass (1)
5	7500	5	E60	12.7	4.61	Pass (1)
6	7500	1	E70	12.7	0.79	Pass (1)
7	18750	3	E70	7.85	5.93	Pass (1)
8	7500	5	E70	3	3.95	Fail (0)
9	30000	5	E60	3	18.45	Fail (0)
10	18750	3	E60	7.85	6.92	Pass (1)

4. FINITE ELEMENT ANALYSIS

The specimen FEA model is created similarly to the study [5]. Single-sided groove butt weld is made between both halves of the specimen. The left end of the specimen is fixed, and tensile load is applied on the right end. The default software mesh setting is used for the finite element analysis, as shown in Fig. 2.

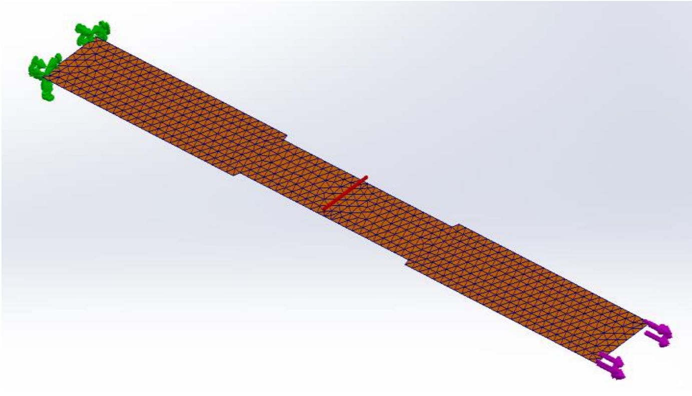

Fig-2: Screenshot of loading of the specimen

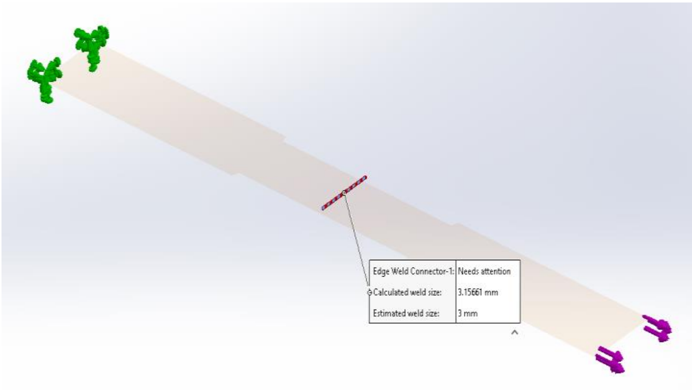

Fig-3: Screenshot of displayed required weld size of the specimen

As per the run order shown in Table 2, the values of the input variables are changed to perform the simulation study in the SolidWorks software. The value of the required weld size obtained (as shown in Fig. 3) from the simulation study is recorded in column 6 of Table 2.

5. RESULTS

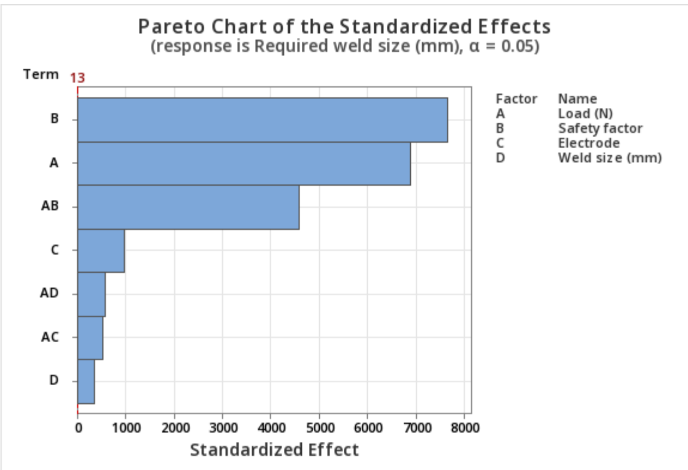

Fig-4: Pareto chart showing the significant parameters

The Pareto chart (Fig. 4) and ANOVA table 3 show that safety factor, load, electrode, weld size, interactions of load and safety factor, load and electrode, and load and weld size are significant at α = 0.05.

TABLE-3: ANALYSIS OF VARIANCE (ANOVA) OF LOAD, SAFETY FACTOR, ELECTRODE AND WELD SIZE WITH REQUIRED WELD SIZE AS RESPONSE

Source	**DF**	**Adj SS**	**F-Value**	**P-Value**	**% Contribution**
Load (N)	1	118.965	47586125	0	**36.83%**
Safety factor	1	146.804	58721645	0	**45.45%**
Electrode	1	2.44	976144	0.001	**0.76%**
Weld size (mm)	1	0.308	123245	0.002	**0.10%**
Load (N)*Safety factor	1	52.891	21156245	0	**16.38%**
Load (N)*Electrode	1	0.702	280845	0.001	**0.22%**
Load (N)*Weld size (mm)	1	0.865	345845	0.001	**0.27%**
Curvature	1	0	1	0.5	0.00%
Error	1	0			0.00%
Total	9	322.975			100.00%

ANOVA table 3 shows that the safety factor has a maximum contribution of 45.45%, followed by load and interaction of load and safety factor contributions of 36.83% and 16.38% towards required weld size, respectively.

The mathematical model of the required weld size equation with an R-square value of 100% is,

Required weld size (mm) = 0.57003 + 0.000047 Load (N) - 0.000833 Safety factor - 0.00025 Electrode + 0.072509 Weld size (mm) + 0.000114 Load (N)*Safety factor - 0.000026 Load (N)*Electrode - 0.000006 Load (N)*Weld size (mm) (1)

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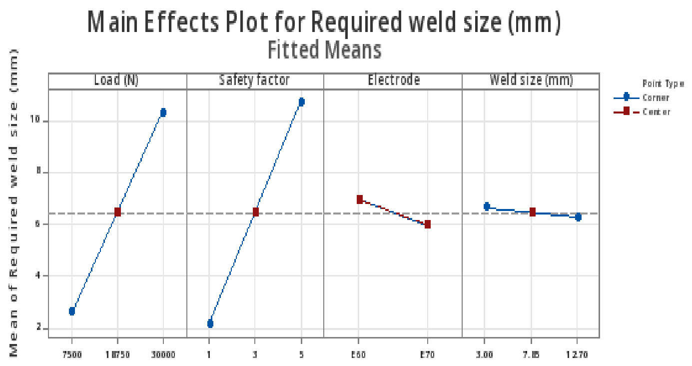

Fig-5: Main factorial plot of load, safety factor, electrode, weld size and the required weld size

An increase in load leads to an increase in the required weld size. Second, the increase in safety factor also leads to an increase in the required weld size. Third, electrode E60 leads to a higher required weld size than electrode E70. Fourth, the effect of selected weld size is almost negligible. However, the electrode and selected weld size contributions to the required weld size are 0.76% and 0.10%, respectively.

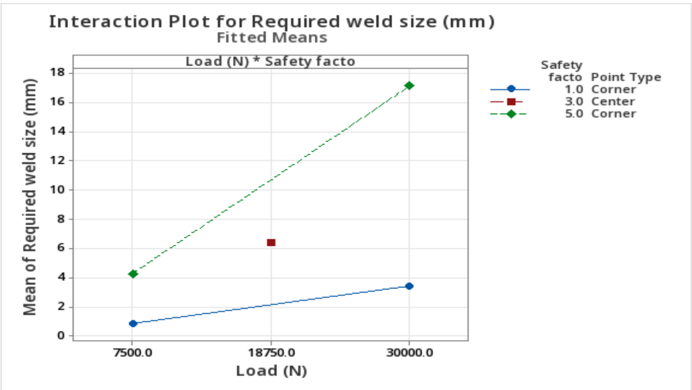

Fig-6: Interaction plot of load, safety factor and the required weld size

The interaction plot in Fig. 6 of the load and safety factor shows that an increase in safety factor and load leads to an increase in the required weld size.

To conduct an optimisation study to minimise the required weld size with pass, the pass and fail values were stored in separate column as 1 and 0, respectively. If the value obtained of the required weld size from the simulation study is less than the selected weld size, it is recorded as pass in column 7 of Table 2 and vice-versa. Fig. 7 shows an optimised value of the load of 30000N, safety factor of 1, E70 electrode, and weld size of 3 mm, which will give a minimum required weld size of 3.1598 mm with a pass.

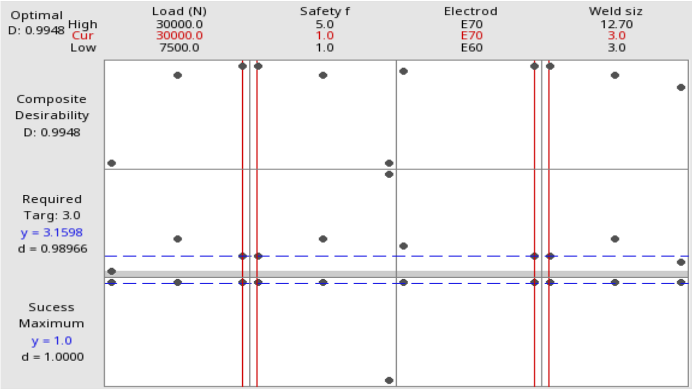

Fig-7: Optimisation results of load, safety factor, electrode, weld size and the required weld size

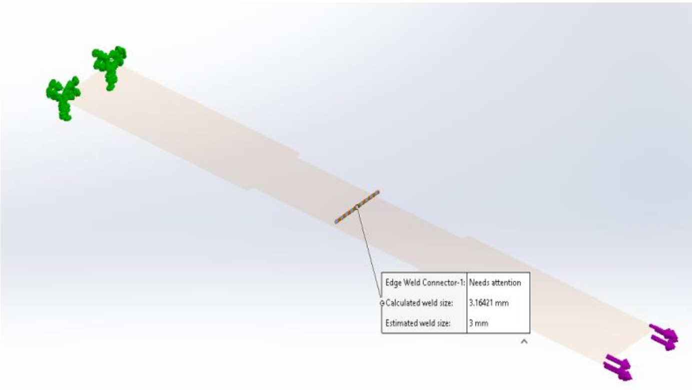

Fig-8: Screenshot of displayed required weld size of the specimen

The optimised load, safety factor, electrode and weld size values were applied to the FEA model. The obtained value of the required weld size is 3.1642 mm, as shown in Fig 8.

6. DISCUSSION

First, the main interaction plot (Fig. 5) shows that the center point does lie on the line joining the start and end points, indicating a linear relationship between the input and response variables. On the other hand, an interaction plot of load and safety factor in Fig.6 shows that the center point does not lie on the lines indicating the presence of curvature. However, the ANOVA Table 3 shows that the effect of the curvature with a p-value of 0.5 is insignificant at α=0.05. Therefore, it is concluded that the relationship between the input variables and the response variable is linear. Hence, the study accepted H_0. It is concluded that half-fraction factorial design is an appropriate optimisation method.

Second, the factorial plot in Fig. 5 shows that an increase in the load leads to an increase in the required weld size. In addition, the ANOVA Table 3 shows that an increase in load makes the second highest significant contribution of 36.83% to an increase in the required weld size at α=0.05.

Therefore, it is concluded that an increase in applied load leads to an increase in the required weld size.

Third, the factorial plot in Fig. 5 shows that an increase in the safety factor leads to an increase in the required weld size. In addition, the ANOVA table 3 shows that an increase in the safety factor makes a maximum significant contribution of 45.45% to an increase in the required weld size at α=0.05. Similarly, the interaction of the load and safety factor makes the third highest significant contribution of 16.38% to an increase in the required weld size at α=0.05, as shown in ANOVA Table 3. In addition, the interaction plot of the load and safety factor in Fig. 6 shows a more significant slope of the safety factor line than the load line slope. As a result, the safety factor effect on the required weld size is greater than the applied load. Therefore, it is concluded that an increase in the safety factor leads to an increase in the required weld size.

Fourth, the factorial plot in Fig. 5 shows that using the E60 electrode leads to a bigger required weld size compared to using the E70 electrode. In addition, the ANOVA Table 3 shows that an electrode type significantly contributes 0.76% to an increase in the required weld size at α=0.05. Therefore, it is concluded that a lower tensile strength electrode leads to a bigger required weld size. This finding agrees with [5] that filler material strength is an essential parameter in welded joints.

Fifth, equation 1 shows the mathematical model R-square value of 100%. The difference in the required weld size values obtained using the mathematical model (3.1598 mm, as shown in Fig. 7) and through the simulation study (3.1642 mm, as shown in Fig. 8) is 0.0044 mm (0.44%). Therefore, it is concluded that the developed mathematical model is capable of predicting the required weld size for a single-sided groove butt joint for the range of the used parameters.

7. CONCLUSION

The study has concluded that the relationship between the input variables and the response variable is linear, and the half-fraction factorial design is an appropriate optimisation method to refine the weld size. Second, an increase in applied load leads to an increase in the required weld size. Third, an increase in the safety factor leads to an increase in the required weld size. Fourth, a lower tensile strength electrode leads to a bigger required weld size. Fifth, the developed mathematical model is capable of predicting the required weld size for a single-sided groove butt joint in the used parameters range.

The limitation of this study is that the data from virtual simulations has been collected for the study. In addition, the single-sided groove dimensions of the butt joint were not designed, neither it has been possible to control the amount of weld penetration in the FEA model. The default weld available in the software is used. Further research may be carried out to compare whether there is any difference in the required weld size as per the American Welding Code and the Euro Welding Code.

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