EXPERIMENTAL EVALUATION OF THE SHEAR STRENGTH OF T-JOINTS IN ASTM A36 STEEL, FILLET WELDED UNDER SMAW PROCESS

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Abstract

This project aimed to experimentally evaluate the shear strength of ASTM A36 steel fillet welds under the SMAW process. Standardised specimens of different thicknesses were obtained for the study. The LRFD method of the AISC 360:2010 was used to determine the theoretical shear strength, for the experimental value a tensile test was performed on the specimens where the fillet weld acts in shear, and the percentage error between the theoretical and experimental values is below 10%. At the same time, the shear strength in the effective area of the fillet weld of the experimental value was checked against table 4.3 of AWS D1.1:2020. Additionally, simulations of the specimens were carried out using the finite element method in ANSYS software and finally, the simulation was validated using the Hourglass energy principle. 1945

Keywords: Test specimens;shear strength; fillet weld; ANSYS; validation; hourglass.

DOINumber:10.48047/nq.2023.21.5.NQ222187 **NeuroQuantology2023;21(5):1945-1960**

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1. Introduction

The present investigation presents a process of experimental evaluation of the resistance to the cut in joints type T with fillet welding under the process of Shielded metal arc welding (SMAW) in steel American Society for Testing and Materials (ASTM) A36, in our country, at the moment the constructions in metallic structure have covered a great occupational and professional field, where the joints of the structural elements depending on different factors such as structural design, operation, the use that they are going to be used can be used in two ways either by welding or bolts in some cases can be used both ways mentioned above, in this research will evaluate the shear strength in fillet welds using the welding process Shielded metal arc welding (SMAW). Fillet welding is used for both T-joints and lap joints, it is worth mentioning that fillet welding is always present in the different metallic constructions with a greater application in the joints between beam-columns.

But as we determine and/or validate if the fillet weld meets the parameters established in the standard, the procedure to experimentally evaluate the weld is established, a Welding Procedure Specification (WPS) must be followed, this pre-qualified WPS is supported in accordance with numeral 5 of the American Welding Society (AWS) D1.1:2020 [1].

Once the experimental evaluation of the shear strength of the fillet weld has been carried out, the experimental results will be admitted by means of a simulation using the finite element method, with the ANSYS software and its complement Explicit Dynamics.

2. Materials and Methods

To carry out the experimental evaluation on ASTM A36 steel specimens by means of a tensile test, the standards used for the sizing of the specimens and welding were the following standards: ASME:2019 section IX - part QB, AWS D1.1:2020, AISC 360:2010.

Several steps were carried out to obtain the experimental results and compare them with the theoretical results, which were then validated using the finite element method "ANSYS" with the Explicit Dynamics add-on and finally the simulation was validated by defining the hourglass energy, figure 1.

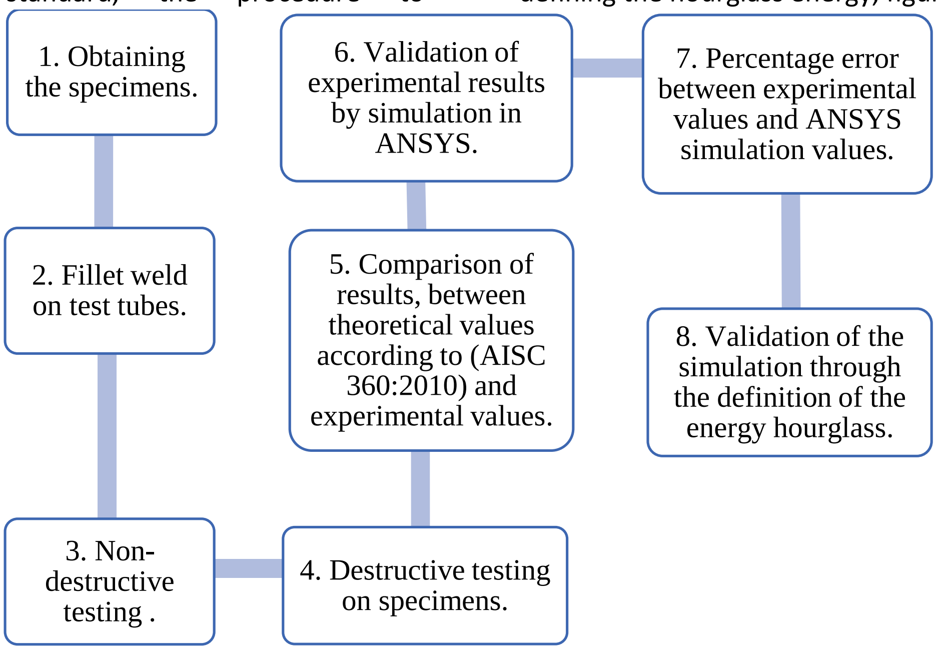


Figure 1. Procedure planned for this technical project.

2.1 Design strength of welds.

At this point the strengths of the fillet weld and CJP (full penetration joint) groove weld are determined, the strength of the welds was calculated according to chapter J using the design strength (LRFD) according to AISC 360:2010 [2].

2.1.1 Effective area in fillet weld

According to clause J2,2a of AISC 360 (2010, p.110), the effective area of a fillet weld shall be the effective length multiplied by the effective throat. The effective throat of a fillet weld shall be the shortest distance from the root of the joint and the hypotenuse of the inscribed triangle as shown in Figure 2 [2].

Therefore:

A_{we}=0,707 w L eq. (1)

Where:

A_{we} = affective area of the weld, in in^2 or (mm^2)

w = weld fillet size or leg, in inches or (mm)

L = effective length of the weld fillet, given by the total length of the complete seam, in inches or (mm).

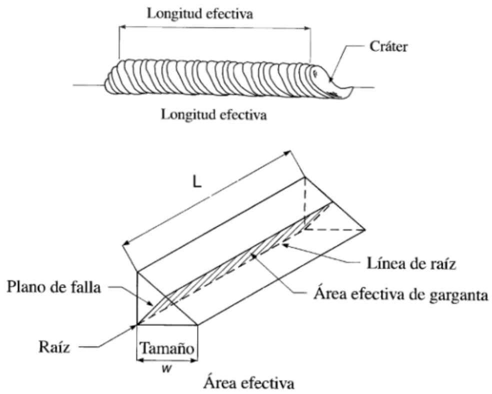


Figure 2. Effective length and effective area of a fillet weld

2.1.2 Design strength (LRFD) of fillet weld according to AISC 360 Chapter J.

According to clause J2.4 of AISC 360 (2010, p.113), the design strength of the fillet weld shall be the lower of the strength of the base material and the weld metal [2]. "$\boldsymbol{\Phi R_n}$" of the fillet weld shall be the lower of the resistance of the base material and the weld metal [2].

The values of Φ should be taken from table J2.5 of AISC 360 (2010, p.114), for the present case we have the value:

$$\Phi = 0.75\ (\text{LRFD}) \qquad eq.(2)$$

According to table J2.5 of AISC 360 (2010, p.115), to determine the nominal shear strength of the weld metal, the following equations apply:

$$F_{nw} = 0{,}60\ F_{EXX} \qquad eq.(3)$$

$$R_n = F_{nw} A_{we} \qquad eq.(4)$$

Where:

F_{nw}= Nominal weld metal stress per unit area, in ksi (MPa)

F_{EXX}= filler metal rating number, in ksi (MPa)

A_{we} = effective area of the weld, in^2 (mm^2)

R_n = shear strength of the weld metal, lbf (N)

ΦR_n = design shear strength LRFD of the weld metal, lbf (N)

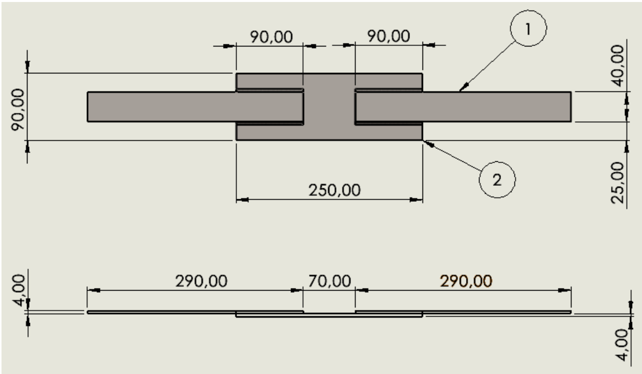
The manual calculation and experimental tests were carried out for three specimens of different thicknesses, each specimen containing three coupons, giving a total of nine coupons for the experimental test.

Table I. Dimensions of the coupons.

Test tubes	Thickness (mm)	Dimensions				N° Test tubes
		Length x width	*Uni.*	*Length x width*	*Uni.*	

		(mm)			*(mm)*			
Coupon 1	4	Plate N°1	290 x 40	2	Plate N°2	250 x 90	1	3
Coupon 2	6		290 x 40	2		250 x90	1	3
Coupon 3	8		290 x 40	2		250 x 90	1	3

Figure 3 shows the dimensions of plates N°1 and N°2 that make up the coupon, the dimensions of the coupons are the same for the different thicknesses, and the size and length of the weld is the one that varies according to the thickness of each coupon.



(Figure 3). Dimensions of the coupons for thicknesses of 4, 6, 8 mm

As shown in table 7.7 of AWS D1.1:2020 which specifies the minimum thickness that can be used in the weld bead [1].

Table II. Minimum sizes for fillet welds.

Table 7.7
Minimum Fillet Weld Sizes (See 7.13)

Base Metal Thichness (T)[a]		Minimum Size of Fillet Weld[b]	
in	mm	in	mm
T ≤ 1/4	T ≤ 6	1/8[c]	3[c]
1/4 < T ≤ 1/2	6 < T ≤ 12	3/16	5
1/2 < T ≤ 3/4	12 < T ≤ 20	1/4	6
3/4 < T	20 < T	5/16	8

Once the dimensions of the specimens were obtained, welding was carried out using the SMAW E-6011 process, in accordance with the WPS specification (Welding Procedure Specification).
The welding parameters that were applied to the specimens are shown below:

Table III. Welding parameters used in the coupons.

Specimens		**PASSAGES**	**PROCESS**	**ELECTRODE (CLASS)**	**ELECTRODE DIAMETER(in)**	**AMPS.**	**VOLTS.**	**VEL. cm/min**	**POLARIZED**
Specimens4 mm	CouponN° 1	1	SMAW	E-6011	1/8	85	22	15	+
	Coupon N°2	1	SMAW	E-6011	1/8	85	22	15	+
	Coupon	1	SMAW	E-6011	1/8	85	21.5	15	+

	N°3								
Specimen s6 mm	CouponN ° 1	1	SMAW	E-6011	1/8	92	22	15	+
	Coupon N°2	1	SMAW	E-6011	1/8	92	23	15	+
	Coupon N°3	1	SMAW	E-6011	1/8	92	22	15	+
Specimen s8 mm	CouponN ° 1	1	SMAW	E-6011	1/8	105	23	11.5	+
	Coupon N°2	1	SMAW	E-6011	1/8	105	23.5	11.5	+
	Coupon N°3	1	SMAW	E-6011	1/8	105	23.5	11.5	+

According to the above parameters, the nine coupons for the experimental test of the shear acting fillet weld were obtained.

Figure 4. Welding cawasrried out on the coupons.

2.2 Non-destructive testing (NDT) inspection

Three types of NDT were carried out, and all played a fundamental role in order to rule out defects, diandscontinuities in the weld seams; in each te,st the procedure was applied according to the standard that governs it, once the data was taken it was verified with the AWS D1.1:2020 standard, which determines whether the weld is accepted or rejected.

2.2.1 Visual inspection.

Once the visual inspection procedure has been performed in accordance with AWS B1.11 (2000, p.2), and checked against AWS D1.1 (2020, p.219) clause 8.9, the weld of all specimens is accepted [1, 6].

Figure 5. Visual inspection.

2.2.2 Inspection by means of penetrant inks.

Once the procedure was performed using penetrant dyes which by the principle of capillary action identifies if there is any surface defect in the weld bead according to ASTM E 165 (2012, p.3), and checked with the AWS D1.1 (2020, p.219) numeral 8.10, the weld of all specimens is accepted [1, 7].

Figure 6. Inspection using penetrant inks.

2.2.3. Magnetic particle inspection.

Once the magnetic particle procedure was performed in accordance with ASTM E 709 (2001, p.3)and tested in accordance with AWS D1.1, paragraph 8.10. (2020, p.219)the welding of all specimens is accepted [1, 8].

Figure 7. Magnetic particle inspection.

2.3 Tensile test on coupons.

Each coupon was placed in the universal machine by correctly clamping the outer plates of the coupons with the jaws, the upper jaw clamping the upper plate and holding it in place, while the lower jaw clamps the lower plate so that the coupons are pulled downwards, and the fillet weld is shear-welded.

Figure 8. Tensile test on the 4-, 6- and 8-mm coupons respectively.

Simulation

To carry out the simulation, ANSYS software was used, where an explicit dynamic analysis model was proposed using the Explicit Dynamics complement. The procedure followed was as follows:

- Problem definition
- Pre-process
- Process
- Post process

The problem has been defined as the elaboration similar to the experimental tensile test using ANSYS with the Explicit Dynamics add-on, the pre-processing consists of several steps among them:The definition of the base material, filler material, meshing and mesh quality, in this case each material must contain the mechanical characteristics that define it as such, the definition of the geometry of both the base material and the filler material, which in this case is the weld bead, imitating the shape and dimensions of the physical specimens. 1951

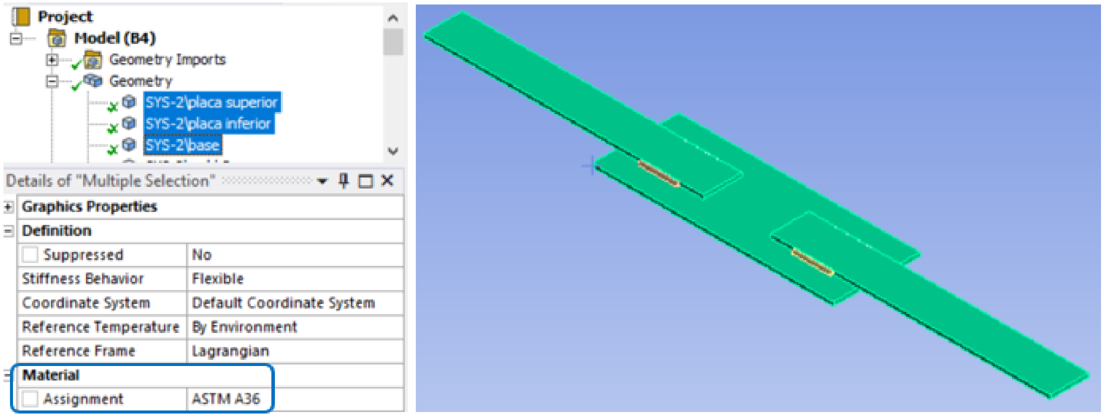


Figure 9. Allocation of base material and filler material.

Mesh definition: degenerate shapes of solid elements and layers (such as a triangular layer or a tetrahedral solid) are avoided. They are usually too rigid and less precise than quadrilateral and hexahedral shapes. Try to achieve a mesh with uniform element sizes (i.e. avoid areas with relatively small elements) [3].

According to the geometry of the specimens, the tools used in the software are those shown in the following illustration and an extremely fine mesh quality was obtained with a mesh size of 2 mm over the entire element, this means that the model was divided into zones of 2 mm^2 for the software to solve the mathematical model and avoid errors at the time of the simulation, the mesh used is the same for the three different thicknesses of each specimen specifically 4, 6 and 8 millimetres.

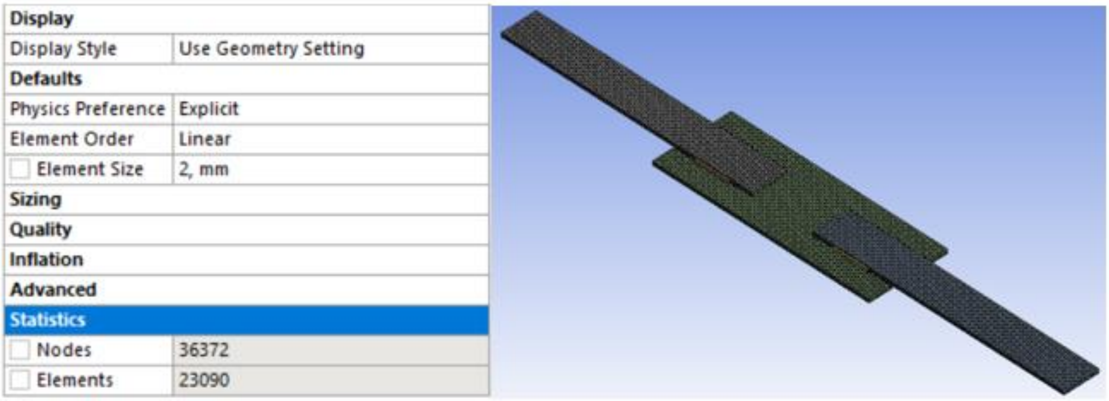


Figure 10. Definition of the grid.

Finally, to simulate the tensile tests, the operation of the Universal Machine is considered, which has a fixed head and a mobile head. For this purpose, a fixed support at one end of the specimen and a mobile displacement at the other end have been introduced as boundary conditions in order to generate the traction in the specimen and cause the shear in the weld bead.

3. Results and Discussion

The result obtained by the Laboratory of Stress and Vibration Analysis of the National Polytechnic School is as follows.
Where:
FJS: welded joint failure
FMB: failure of base material

Table IV. File weld shear test for 4 mm specimens.

Id	**Maximum registered load**		**Obs.**
	lbf	**N**	
M22.054.01	16 541	73 578	FMB
M22.054.02	16 687	74 226	FJS
M22.054.03	16 689	74 235	FJS

The shearing that occurred in the fillet weld was clearly evident, where the average maximum load recorded was F = 16 639 lbf; 74 013 N

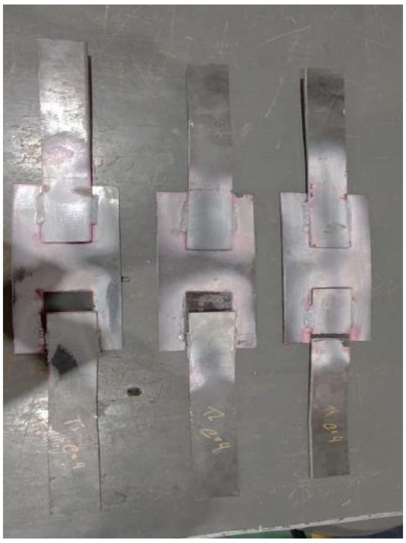


Figure 11. 4mm sockets after tensile test

Table V. File weld shear test for 6 mm specimens.

Id	Maximum registered load		Obs.
	lbf	N	
M22.054.04	20 417	90 820	FJS
M22.054.05	20 772	92 401	FJS
M22.054.06	16 765	74 573	FJS

Clearly evident was the shearing that occurred in the fillet weld, where the average maximum load recorded was F = 19 318 lbf; 85 931.33 N

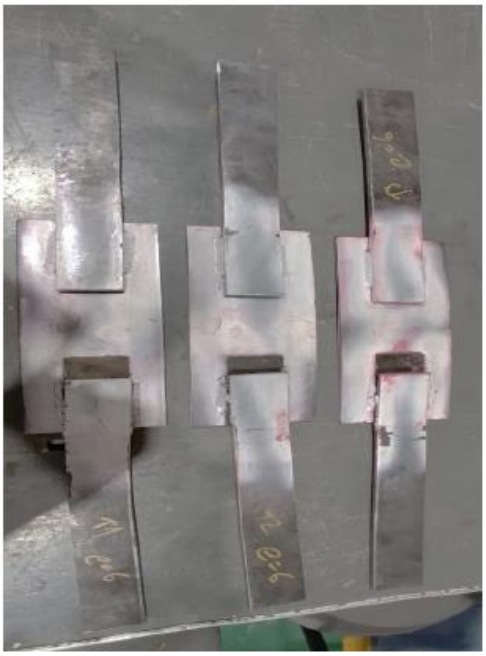


Figure 12. 6mm sockets after tensile test

Table VI. File weld shear test for 8 mm specimens.

Id	Maximum registered load		Obs.
	lbf	N	
M22.054.07	23 985	106 689	FJS
M22.054.08	24 467	108 834	FJS
M22.054.09	25 265	112 384	FJS

The shearing that occurred in the fillet weld was clearly evident, where the average of the mean maximum load recorded was F = 24 572.33 lbf; 109 302.33 N

Figure 13. 8 mm sockets after tensile test.

The comparison of results was made between the theoretical values obtained for shear strength using equations 2, 3 and 4 of this project and the experimental values obtained in the fillet weld shear test. A single value is used for both the theoretical value and the experimental value, since in the case of the theoretical values the values obtained are valid for the three coupons of each thickness respectively; while the experimental values use the average of the maximum load recorded for each thickness.

Table VII. Comparison between theoretical Rn and experimental Rn

Test tubes	thickness (mm)	Theoretical Rn (N)	Experimental Rn (N)	Theoretical Rn (lbf)	Experimental Rn (lbf)
Test tube N°1	4	75 992.44	74 013	17 083.78	16 638.78
Test tube N°2	6	85 041.49	85 931.33	19 118.09	19 318.13
Test tube N°3	8	119 688.03	109 302.33	26 906.94	24 572.14

Percentage error between theoretical resistance and experimental resistance

The actual percentage error between the theoretical shear strength and the experimental shear strength is calculated according to the values recorded in table VII.

Table VIII. Percentage errors of the specimens.

Test tubes	thickness (mm)	Error
Test tube N°1	4	2.13
Test tube N°2	6	1.03
Test tube N°3	8	9,5

According to the percentage errors shown in table VIII, an average error of 4.22% was obtained.

3.1. Experimental shear strength testing of fillet weld in accordance with table 4.3 of AWS D1.1:2020

The shear strength of fillet welds can also be tested as described in table 4.3 of AWS D1.1 (2020, p.32) [1].

According to the INDURA manual (2014, p. 1) the tensile strength of the E-6011 electrode is 495 MPa or 71 794 psi, where 30% of the tensile strength of the mentioned electrode represents the 21 538 psi [9].

The stress in the fillet weld of each coupon tested was calculated.

$$\sigma_{exp} = \frac{F}{A} \qquad eq. (5)$$

Where:

σ_{exp} = effort in fillet welding.

A = area of the weld.

F = maximum load recorded in the experimental test.

0.30*σ_{E-6011} = 21 538 psi.

Table IX. Validation of experimental results of fillet weld according to table 4.3 of AWS D1.1 (2020, P.32)

Specimens tested for fillet weld shearing		**Maximumregistered load(Lbf)**	**σ exp (psi)**	**0.30 * σ (electrode)**	**If V. exp ≥ V. theo."Complies"**	
					YES	**NO**
Specimens4 mm. (A=0.5239in²)	Coupon N° 1	16 541	31 573	21 538	x	
	Coupon N°2	16 687	31 851	21 538	x	
	Coupon N°3	16 689	31 855	21 538	x	
Specimens6 mm. (A=0.5907in²)	Coupon N° 1	20 417	34 564	21 538	x	
	Coupon N°2	20 772	35 165	21 538	x	
	Coupon N°3	16 765	28 382	21 538	x	
Specimens8	Coupon N°	23 985	28	21 538	x	

mm. (A=0.8314in^2)	1		849			
	Coupon N°2	24 467	29 429	21 538	x	
	Coupon N°3	25 265	30 389	21 538	x	

3.2. ANSYS simulation result

This section shows the results of the simulations and validations carried out on the respective fillet weld shear test specimens, where the value obtained experimentally is validated in the ANSYS software and the Explicit Dynamics complement was used.

The value with which the fillet weld shear was obtained in the simulations is compared to the value obtained experimentally, and percentage errors below 10% were achieved.

Table X. Percentage error between experimental force and simulation force on test specimens

Specimens	Experimental test. Maximum recorded load (N)	Simulation: ANSYS. Maximum registered load (N)	Error
Specimen4mm	74 013	79 200	6.54
Specimen6mm	85 931.33	94 300	8.87
Specimen8mm	109 302.33	119 900	8.84

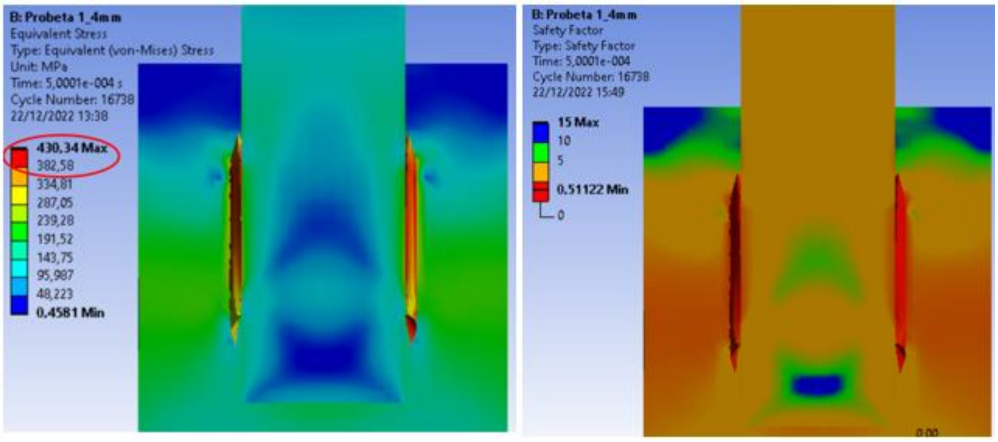


Figure 14. Evidence of the cut in the fillet weld, 4 mm test piece.

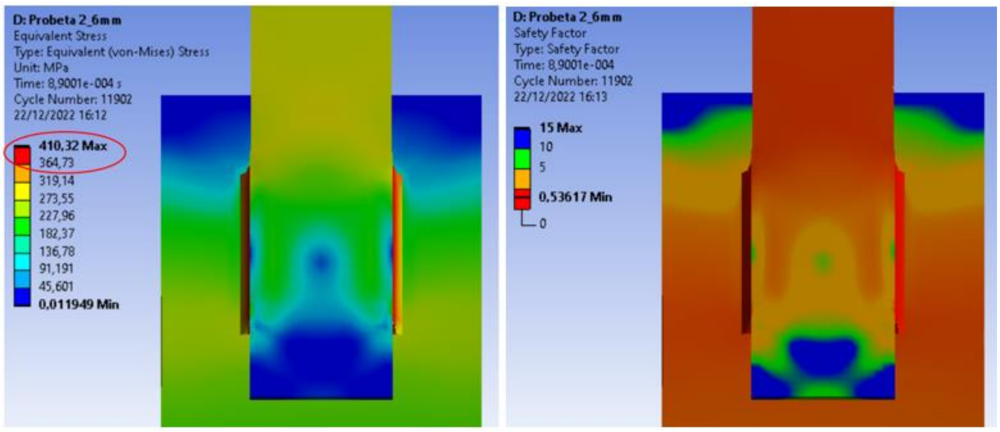


Figure 15. Evidence of cutting in fillet weld, 6 mm specimen.

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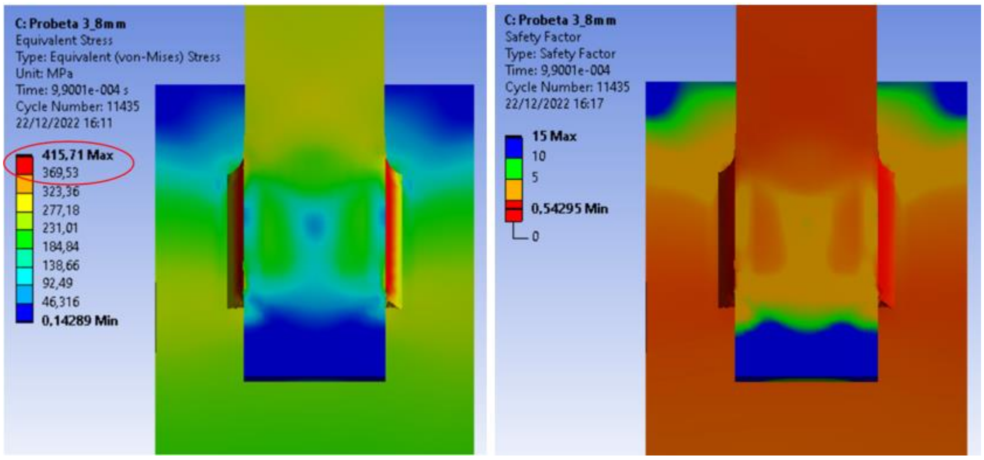

Figure 16. Evidence of the cut in the fillet weld, 8 mm specimen.

3.3. Approval of the simulation using hourglass energy.

It was analysed using the hourglass energy principle where ANSYS (2004, p.116) mentions that, when performing an Explicit Dynamics analysis, the hourglass energy should not exceed 10% of the internal energy [3].

The hourglass energy of the 4-millimetre specimen was analysed, where it is clearly represented that it does not exceed 10% of the internal energy, since 10% of the internal energy is 52.35 J, and the hourglass energy is approximately below 40 J.

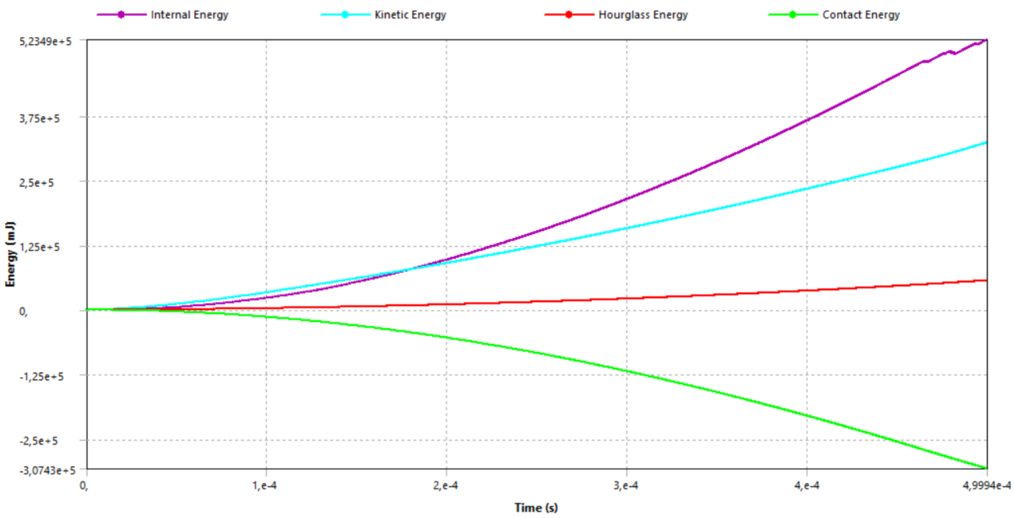

Figure 17. Summary of energies, 4mm specimen

The hourglass energy of the 6 millimetre specimen was analysed, where it is clearly represented that it does not exceed 10% of the internal energy, since 10% of the internal energy is 69.7 J, and the hourglass energy is very significant.

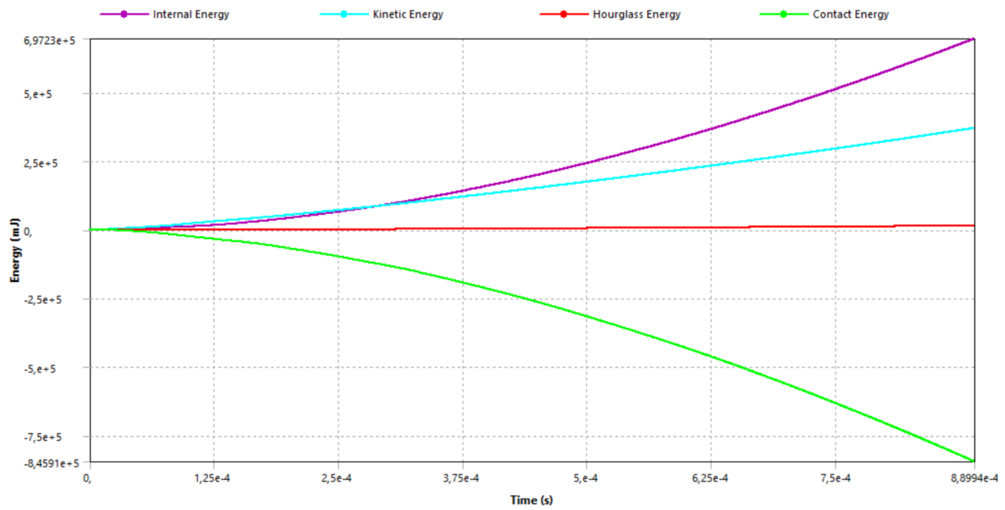

Figure 18. Summary of energies, 6mm specimen

The hourglass energy of the 8-millimetre specimen was analysed, where it is clearly shown that it does not exceed 10% of the internal energy, since 10% of the internal energy is 109 180 mJ, and the hourglass energy is practically zero.

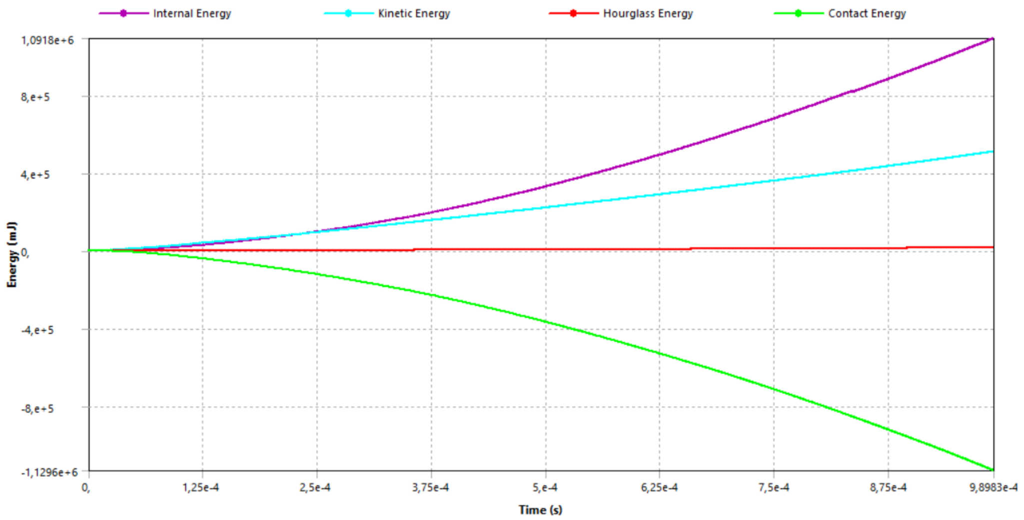

Figure 19. Summary of energies, 8 mm test specimen

4. Conclusion*s*

Based on the analysis it is seen that the application of standards ensures good welding performance therefore the application of standards, use of the respective WPS (Welding Procedure Specification), WPQ (Welder Skill Qualification), NDT (Non-Destructive Testing) and the use of qualified personnel to execute the welding procedures is mandatory.

By using the minimum fillet sizes for the weld bead it was clearly shown that despite using the minimum values the shear strength of the weld meets the requirements of AWS D1.1, however, it is possible to use fillet sizes that exceed the minimum to obtain a higher degree of shear strength in the beam-column joints.

The experimental resistance of the fillet weld meets the specifications detailed in AWS D1.1:2020, which states that the shear strength of the fillet weld should be at least 30% of the resistance of the electrode used.

When simulating the coupons in ANSYS, a higher force was required than the one obtained experimentally. This may be because the geometrical model of the coupon does not present any type of defect in the material or in the weld that may be present in the physical model and cannot be seen with the naked eye by the user.

The results obtained experimentally when compared with the theoretical results and validated by means of finite elements, have an error of less than 10% in all simulations and comply with the hourglass definition that validates these simulations.

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