Mechanical Properties of Welded Deformed Reinforcing Steel Bars

Ghafur H. Ahmed

Department of Highway Engineering, Technical Engineering College, Hawler Polytechnic University
Erbil, Kurdistan Region - F.R. Iraq

***Abstract*—Reinforcement strength, ductility and bendability properties are important components in design of reinforced concrete members, as the strength of any member comes mainly from reinforcement. Strain compatibility and plastic behaviors are mainly depending on reinforcement ductility. In construction practice, often welding of the bars is required. Welding of reinforcement is an instant solution in many cases, whereas welding is not a routine connection process. Welding will cause deficiencies in reinforcement bars, metallurgical changes and re-crystallization of microstructure of particles. Weld metal toughness is extremely sensitive to the welding heat input that decreases both of its strength and ductility. For determining the effects of welding in reinforcement properties, 48 specimens were tested with 5 different bar diameters, divided into six groups. Investigated parameters were: properties of un-welded bars; strength, ductility and density of weld metal; strength and ductility reduction due to heat input for bundled bars and transverse bars; welding effect on bars' bending properties; behavior of different joint types; properties of three weld groove shapes also the locations and types of failures sections. Results show that, strength and elongation of the welded bars decreased by (10-40%) and (30-60%) respectively. Cold bending of welded bars and groove welds shall be prevented.**

***Index Terms*—Deformed bar, heat input, strength and ductility reduction, welding, weld groove.**

I. Introduction

In the second half of the nineteenth century, the possibility of using reinforcement bars to reinforced concrete was found (Nilson, H., Darwin, D. and Dolan, W., 2004). From that time to now, thousands of studies have been performed on the reinforcement bars for determining the best performance of reinforcement in the concrete. In many cases of concrete building construction, it is required to weld concrete reinforcement for several reasons, as for anchors, dowels or lap splices. Welding also be may require in composite structural steel and reinforced concrete structures and during alterations in reinforced concrete or repairs in building. In all cases considerations such as stress level in the bars, consequences of failure and heat damage to existing concrete due to welding operations needs precautions and special restrictions must be placed both on the type of steel used and the welding procedures (Omer, et al., 1999; Marten, 2004; Franchi and Crespi, 2007; ACI 318, 2011).

For structural steel construction purposes welding is a very effective means to connect two or more pieces of materials together (Wai, and Eric, 2005; AWS A3.0M, 2010). Whereas, welding of reinforcing bars result in metallurgical changes that reduce yield and ultimate strength, ductility, toughness and bendability (Serna, et al., 2002; Hakansson, 2002; Nikolaou and Papadimitriou, 2004; CRSI, 2004; Nurnberger, 2005). During welding process, there is an interference of many factors that are all combined in the same time, factors and actions mainly effect welding may be mechanical, geometrical and chemical properties of reinforcement bars and welding electrodes, thermochemical and electrochemical actions, thermal stresses and welding fusion pressure and heat. Considering all of the mentioned actions means, there is still unknown reaction of the welded bars during and after welding has been finished; the unknowns shall be found by experimental evidence and research (Kim, et al., 1987; Alk, Savvopoulos. and Dimitrov, 2001; Franchi and Crespi, 2007).

II. Scope of the Work

Welding of deformed reinforced bars ASTM A615-09b (2009) tested according to ASTM A370-10 (2010) having diameters 8-25mm subjected to tensile stress. Clean bars, non-corroded nor coated, plain bars were excluded. Welding procedure and welding electrodes must be according to AWS A5.1M (2012). Welding thickness is the filled space between the ribs of the two bundled or lapped bars and both faces. Length and width of welding varies according to the bar diameter and the case studied.

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Corresponding author's e-mail: eng.ghafur.ahmed@gmail.com

III. Research Significance

In concrete building construction, sometimes it is required to weld concrete reinforcement for several reasons, like: headed anchors or dowels in footing, lap splices in slabs, beams, columns or staircases, also may be in composite structural steel-reinforced concrete structures. In residential houses projects, the engineers permit to weld metal doors or windows to the main beam or column reinforcement. It is common to weld reinforcement ties, stirrups and splices in seismic resistance buildings for post ultimate behaviors (Omer, et al., 1999; ACI 318, 2011). As welding of reinforcement is used in construction, therefore it is of great interest for designers and site engineers to have comprehensive idea, that how the welding will affect the mechanical properties of the welded bars interim of weldability, bendability, toughness and ductility (Omer, et al., 1999; Achillopoulou, Pardalakis and Karabinis, 2013).

IV. Problem Statement

In many cases, it is necessary to weld to existing reinforcing bars in a structure. It should be determined if precautions are in order, based on considerations such as stress level in the bars, consequences of failure, and heat damage to existing concrete due to welding operations (ACI 318, 2011). Welding of bars should be performed in accordance with AWS D1.4 (2011), whereas welding of wire or welded wire reinforcement to reinforcing bars or structural steel elements is not covered by AWS D1.4 (2011). If such welding are required on a project, the requirements or performance criteria for this welding should specified, the potential loss of yield strength and ductility achieved when reinforcement is heated by welding (Omer, et al., 1999; Popovic, et al., 2010; ACI 318, 2011). These potential concerns are not an issue for machine and resistance welding as used in the manufacture of welded plain and deformed wire reinforcement covered by ASTM A1064M-10 (2010).

V. Welding Deformed Reinforcing Bars in ACI 318 Code (2011)

For understanding the code special considerations regarded to welding, the code provisions for welded and un-welded deformed reinforcement shall be compared. For this purpose the following cases can be discussed:

ACI 318-11 12.7 & 12.2

development length of welded bars is development length of un-welded bars times welding factor *(ψ_w)*, see (1), the factor is always (1.0), except when across bar exist in development length and this bar is at least 50mm away from critical section.

$$\psi_w = \left(\frac{f_y - 240}{f_y} \geq \frac{5d_b}{s}\right) \leq 1.0 \qquad (1)$$

ψ_w: factor used to modify development length for welded deformed wire reinforcement in tension, f_y (MPa): yield strength of the welded bar. d_b (mm):nominal diameter of bar and, s (mm): is the spacing between the bars to be developed.

ACI 318-11 12.18 & 12.15

Lap splice required same length for welded and un-welded when provided reinforcement is less than double of that required by analysis (class B), for provided area more than double of required by analysis (class A), welded splices require 30% more length, bars of diameters larger than 16mm shall be increased by 50% (12.19). The overlap measured between outermost cross wires of each reinforcement sheet shall be not less than 50 mm (12.18.1). The total tensile force that can be developed at each section must be at least twice that required by analysis, and at least 140 MPa times the total area of reinforcement provided (12.15.5.3).

ACI 318-11 12.17

For column splices, butt welding can be applied but when stress level in the bars is ($\leq 0.5f_y$) for class A and B depending on area, whereas stress level is ($> 0.5f_y$) shall be class B, which is increased in splice length by 30%.

From the above comparisons, the following principles can be drawn, to prevent bond failure between weld metal and reinforcing bar;

1) Shorter development length or splice required, means stronger bond provided.
2) Smaller f_y leads to smaller ψ_w then shorter bond length required, means stronger bond exist, i.e. smaller fy leads to stronger bond in welded bars, for constant other parameters.
3) Smaller bar diameters, smaller ψ_w, shorter bond length required, stronger bond exist.
4) Cross bars can carry a stress component in tensioned bars, so the bond length can be reduced, whereas for the same length, the bond for welded bars with cross bars is stronger.
5) Cross bars less than 50 mm away from critical section are not effective and their mechanical properties also will be disturbed, due to the welding heat input.
6) When stress levels are low ($0.5f_y$) in the bar, butt welding which is relatively weak welding type for reinforcing bars is permitted, means technical welding always over that stress level i.e. $0.5f_y$ is 275MPa, 260MPa and 210MPa for G550, G520 and G420 respectively.
7) Minimum length of welding stated in ACI 318 (2011) is 50mm. Developed welded section shall transfer at least double required by analysis or 140MPa, i.e. minimum possible welded strength is 140MPa.

VI. Experimental Investigation

Experimental program illustrate the materials used, testing machines and the parameters investigated in the present research.

A. Materials

Commonly used materials in construction projects were used for the data to be really reflecting the true practical case.

Welding Electrodes

Welding electrodes were manufactured by Golden Bridge welding materials group, Tianjin Yanqiao welding materials co. ltd, of type J38.12, with Ø3.2mm and 350mm length, conformed to GB/T 5117-2012, GB E4313 and AWS A5.1 E6013 as well as ISO 9001. The properties of the electrodes are shown in Table I.

TABLE I
PROPERTIES OF THE WELDING ELECTRODES E6013 AND AWS A5.1M (2012) SPECIFICATIONS

Chemical composition of deposition metal (%)					
Element (%)	C	Mn	Si	S	P
Manufacturer test	≤ 0.12	0.30-0.60	≤ 0.35	≤ 0.035	≤ 0.040
Specification	≤ 0.20	≤ 1.20	≤ 1.00	-	-
Mechanical Properties of Deposition Metal					
Parameter	Fy (MPa)	Fu (MPa)	Elongation (%)	Impact value, KV_2 (J) (0°)	
Manufacturer test	340	460-540	18-26	50-75	
Specification	≥ 330	≥ 430	≥ 17	≥ 47	

Reinforcement Bars

Deformed concrete reinforcing bars were used and tested according to ASTM A370-10 (2010). The measured parameters and the tested properties of the bars compared to ASTM A615-09b (2009) were shown in Table II and Table III, respectively.

B. Machines and Tools

Tensile Testing machine

Material Testing Equipment – Yuksel Kaya Makina, 600 kN capacity and 0.1 kN resolution.

Bending test machine

Universal Testing Machine – Controls, test range Ø6 to Ø32mm.

Welding Machine

AC Arc Welder- BX1-1000, 3-Phase model, dual mode voltage 220V and 380V, Current 180-1000 A.

Weighing Balance

CWT22 Dikomsan; 30kg capacity and 0.1g resolution.

Vernier Caliper

Mechanical Vernier; 200 mm capacity and 0.02 mm resolution.

C. Investigated Parameters

Mechanical tests were performed according to ASTM 370-10 (2010) and welding procedure was according to AWS D1.4 (2011) for all the bars welded, the welding consist of single pass and double welded faces (Hakansson, K., 2002), with filling the space between ribs, and one bar diameter left un-welded for both welded ends.

Group-1: Normal tests (15 specimens)

For determining the normal reinforcement mechanical bar properties, yield strength, ultimate strength, elongation and bending. Also the nominal parameters were measured, like: diameter, area, perimeter, mass, deformation and rib dimensions. Bar diameters were 8, 10, 12, 16 and 25mm, three specimens for each of the bar diameters were averaged.

Group-2: Welding strength (9 specimens)

Three specimens for each of the bar diameters: 8, 12 and 25 mm were used for finding the welding strength. For this purpose 10 mm length between two straight end bars was filled with melted pure weld, having the same bar cross sectional area. Since the welding has not a homogeneous matrix of particles, and it may be changed by specimen size effect, three specimens were averaged for each diameter.

Group-3: Strength and ductility reduction (9 specimens)

For investigating the effects of welding inputted heat, two bars in each of 10, 12 and 16 mm diameters were welded together for double face full length (500 mm) except a gap of 20, 100 and 200 mm was remained un-welded in the center of the bar. The group must determine the results of failure location and its distance away from welding edge, reduction in yield and ultimate strengths and as well as elongations.

Group-4: Transverse bars (3 specimens)

To study the effects of transverse reinforcement bars (like BRC mesh), three 16mm bars were tested having transverse 16mm cross bars with 150mm length. For first specimen one bar was welded in the center of tension, second specimen have two bars 50 mm away from the center and the third specimen has three welded bars, one in the center and another’s are 100mm away from the center (ASTM A184M, 2005). All bars were welded in the four contact points (i.e. right, left, top and bottom).

Group-5: Bend test (9 specimens)

For understanding the effects of the welding on the properties of reinforcement bars subjected to bending test, three bars with 8, 12 and 25mm diameters and 700mm length, were tested by three ways, normal, lap welded and link welded. Welding length in the both cases was 100mm.

Group-6: weld groove shape (3 specimens)

For investigating the best end cut shape before welding, 16mm bars were tested for three section cuts, namely straight ends, square (‖) shape, bevel (I/) shape and (V) shape. Inclined surfaces were 45° from vertical edge and the welding lengths were 32mm (Omer et al., 1999; Wai, C. and Eric, M., 2005).

VII. WELDING AND WELDABILITY

The welds made by the welding machines are electric resistance welds. This type of weld results from a fusion process that uses a combination of pressure and heat generated by electric impulses. In other words, the intersections of the steel bars and the welding electrodes are fused together. No foreign matter is introduced in the welding process (Omer, et al., 1999; CRSI, 2004).

Welding electrodes are classified to several hundred types (AWS A5.1, 2012); each kind has been specified for strength/welding position/coating material. In this work and similar studies (Nikolaou and Papadimitriou, 2004), electrodes of E6013 type were used which means: E indicates that this is an electrode. 60 indicate how strong this electrode is when welded, measured in (ksi). 1 Indicates in what welding positions it can be used (flat, horizontal, vertical, overhead). 3 Indicates the coating, penetration, and current type used.

E6013 coating is rutile potassium, with light penetration, current type: AC/DC (Weld-D-Arc, 2013). All position welding titanium low hydrogen type electrodes with ferrous powder in the coating. It has high welding efficiency, smooth appearance, stable arc and negligible spatter loss (Lincoln E., 2014).

In general, the strength of the electrode used should equal or exceed the strength of the steel being welded (AWS D1.4M, 2011). Finished welds should be inspected to ensure their quality. Inspection should be performed by qualified welding inspectors. A number of inspection methods are available for weld inspections, including visual inspection, the use of liquid penetrants, magnetic particles, ultrasonic equipment, and radiographic methods (Omer, et al., 1999; Wai and Eric, 2005; AWS A3.0M, 2010).

The used welding type was SMAW (Shielded Metal Arc Welding). SMAW is an arc welding process with an arc between a covered electrode and the weld pool (Nurnberger, 2005; AWS A5.1M, 2012; James, 2013). The process is used with shielding from the decomposition of the electrode covering, without the application of pressure, and with filler metal from the electrode (Bohler, 2005). SMAW is often used for bar-bar welding (Nikolaou and Papadimitriou, 2004) and it is filler material could be E6013 (AWS A5.1M, 2012). The minimum allowed preheat and interpass temperature is 27°C, whereas, best performance for preheat temperature is 150°C for Ø19mm and smaller, and 260°C for Ø22mm and larger (AWS D1.4M, 2011). Welding shall not allow below 4°C. In cold weathers preheating to reach to at least 27°C shall be applied. Cool down rate shall not exceed 55°C/hour (AWS A3.0, 2010; Lincoln E., 2014). Increasing in welding speed decreases the welding heat input and chance of formation of defects in weld metal. Whereas, decreasing the welding speed increases the hardness and yield strength of the base metal (Bahman and Alialhosseini, 2010); therefore, the travel speed of 15-45 cm/min is recommended (AWS A3.0, 2010; Lincoln, 2014).

As the technical welding is a sensitive process, the welder shall have an experience of the welding parameters like polarity, porosity, penetration, surface condition, welding sequence (Omer et al., 1999) and the factors that effect of producing best aspect and performance welding; in present study the welder has an experience of 31 years of welding. Performance of the welding is directly related to the amount of heat input during welding process, energy input depend on the factors shown in Eq.2 (GLA, 2000; Marten L., 2004; Popovic et al., 2010). Low heat input produce a porous weld and weak bonding, whereas overheating effect reversely on the strength and ductility of the welded bars, optimum E value is 0.7 kJ/mm (Omer, 1999; Popovic, et al., 2010).

$$E=0.06(U \times I \times T)/Lw \qquad (2)$$

E: Energy (heat) inputted (kJ/mm), U: welding voltage (Volts), I: welding current (AMP), T: welding time (min), Lw: weld length (mm).

Thermochemical and electrochemical composition changes are greater at a low than at a high welding speed. Electrochemical reactions are enhanced by higher, total current flow per unit volume of weld metal. Thermochemical reactions at a low welding speed are enhanced by higher temperatures and longer reaction time before solidification (Kim et al., 1987; Bohler W. 2005).

When welding of reinforcing bars is required, the weldability of the steel and compatible welding procedures needs to be considered. The provisions in AWS D1.4 welding code cover aspects of welding reinforcing bars, including criteria to qualify welding procedures (ACI 318, 2011). For steel bars, the carbon equivalent shall be calculated in Eq.3, using the chemical composition shown in the mill test report (Omer, et al., 1999; AWS D1.4M, 2011; EN 1011-1/A1, 2010).

$$CE = \%(C) + \%(Mn/6) \qquad (3)$$

CE: Carbon Equivalent (%), C: carbon content (%), Mn: Manganese (%).

For the used electrodes in this study CE range is 0.17-0.22. If CE is less than 0.53, the reinforcement is intrinsically weldable, if larger, then the hard and brittle microstructural constituents may be formed, these constituents may be detrimental for good behavior of steel to dynamic loading (Nikolaou and Papadimitriou, 2004; Elijah, 2010). Weldability is improved by decreasing the carbon content, increasing the nickel content and by stabilization (Nurnberger, 2005; Popovic, et al., 2010).

VIII. TEST RESULTS

The results for groups of reinforcement bars numbered 1, 2, 3, 4, 5 and 6 are shown in Tables II & III, IV, V&VI, VII, VIII and IX, respectively.

TABLE II
TEST RESULTS OF G1: MEASURED PARAMETERS VS. ASTM A615-09B LIMITATIONS

Bar des. No.	Nominal dimensions*								Deformation requirements (mm)					
	Nominal mass (kg/m)		Diameter (mm)		Cross sectional area (mm^2)		Perimeter (mm)		Maximum average spacing		Minimum average height		Maximum gap**	
	test	spec.	test	spec.	test	spec.	test	spec.	test	spec.	test	spec.	test	spec.
8	0.399	0.394	8.0	8.0	50.8	50	25.3	25.1	4.60	5.6	0.69	0.32	1.20	3.1
10	0.595	0.560	9.8	9.5	75.8	71	30.9	29.9	6.32	6.7	0.50	0.38	1.46	3.6
12	0.850	0.844	11.7	12.0	108.3	113	36.9	37.7	7.66	8.4	0.69	0.48	1.60	4.6
16	1.573	1.552	16.1	15.9	203.6	199	50.6	49.9	9.66	11.1	0.94	0.71	2.50	6.1
25	3.963	3.973	25.4	25.4	504.8	510	79.6	79.8	15.64	17.8	1.37	1.27	3.24	9.7

* The nominal dimensions of a deformed bar are equivalent to those of a plain round bar having the same mass per meter as the deformed bar.
** Chord of 12.5 % of nominal perimeter.

TABLE III
TEST RESULTS OF G1: TESTED PARAMETERS VS. ASTM A615-09B SPECIFICATION

Bar designation No.	Yield strength (MPa)		Tensile strength (MPa)		Elongation (%)		Bending (inner roller diameter, bending angle)	Sample Grade
	test	spec.	test	spec.	test	spec.		
8	675.4	550	782.8	725	11.7	7	Pass: Ø32,180°	G550
10	689.8	550	820.3	725	10.9	7	-	G550
12	617.6	550	742.2	725	17.2	7	Pass: Ø44, 180°	G550
16	447.5	420	654.0	620	17.7	9	-	G420
25	552.7	420	667.1	620	17.6	8	Pass: Ø128, 180°	G420

TABLE IV
TEST RESULTS OF G2, WELD METAL MECHANICAL PROPERTIES

Bar des. No.	Diameter (mm)	Nominal weld area (mm^2)	Mass of weld per 10mm (g)	Weld density (kg/m^3)		Yield strength (MPa)		Guaranteed yield strength & Bar stress level	Ultimate Strength MPa		Combined Elongation (%)	
8	8.07	51.12	4.03	7883		409.5			539.5		2.6	
8	8.03	50.62	3.97	7843	7863	527.9	475.4	409.5 (0.61fy bar)	576.3	558.3	1.9	2.2
8	8.06	51.00	4.01	7863		488.7			559.2		2.1	
12	11.76	108.56	8.56	7885		392.1			563.3		3.1	
12	11.72	107.83	8.42	7809	7850	411.7	415.4	392.1 (0.63fy bar)	428.5	503.4	2.5	2.8
12	11.74	108.19	8.50	7857		442.5			518.3		2.7	
25	25.30	502.47	39.27	7815		356.3			395.1		4.9	
25	25.30	502.47	39.23	7807	7824	315.8	317.5	280.3 (0.51fy bar)	446.2	432.9	5.6	5.4
25	25.36	504.86	39.63	7850		280.3			457.3		5.6	

TABLE V
TEST RESULTS OF G3, STRENGTH REDUCTION

Bar des. No.	Un-welded center gap (mm)	Yield Load					Ultimate Load				
		Un-welded (kN)	Double bar welded (kN)	Welding resisted load* (kN)	Single bar resisted load (kN)	Reduced strength (%)	Un-welded (kN)	Double bar welded (kN)	Welding resisted load* (kN)	Single bar resisted load (kN)	Reduced strength (%)
10	20	52.3	73.1	12.6	30.3	42.1	62.2	100.1	17.2	41.5	33.3
10	100	52.3	79.3	13.6	32.9	37.1	62.2	105.9	18.2	43.9	29.4
10	200	52.3	91.2	15.7	37.8	27.7	62.2	115.0	19.8	47.6	23.5
12	20	66.9	109.5	16.3	46.6	30.3	80.4	138.8	20.7	59.1	26.5
12	100	66.9	112.2	16.7	47.8	28.6	80.4	140.9	21.0	60.0	25.4
12	200	66.9	119.1	17.7	50.7	24.2	80.4	148.4	22.1	63.2	21.4
16	20	91.1	174.8	19.8	77.5	14.9	131.1	249.0	28.1	110.5	15.7
16	100	91.1	175.9	19.9	78.0	14.4	131.1	253.8	28.7	112.6	14.1
16	200	91.1	177.6	20.1	78.8	13.5	131.1	260.8	29.5	115.7	11.7

* Calculated from the true applied stress, which is uniformly distributed over the bars and the welded area.

TABLE VI
TEST RESULTS OF G3, DUCTILITY REDUCTION AND FAILURE DATA

variables		Elongation			Welded length in half of tension range (mm)	Failure location from weld edge (mm)	Welded strength		Grade	
Bar des. No.	Un-welded center gap (mm)	Un-welded (%)	Welded vs. specification (%)	Reduction (%)			Yield strength (MPa)	Ultimate strength (MPa)	Normal	Welded*
10	20	10.9	04.2 < 11	61.5	90	50	399.6	547.3	550	Fail
10	100	10.9	05.0 < 11	54.1	50	51	433.9	579.0	550	Fail
10	200	10.9	06.1 < 11	44.0	00	45	498.5	627.8	550	Fail
12	20	17.2	06.7 < 12	61.0	90	48	430.2	545.6	550	Fail
12	100	17.2	08.2 < 12	52.3	50	45	441.3	553.9	550	Fail
12	200	17.2	10.3 < 12	40.1	00	48	468.0	583.4	550	Fail
16	20	17.7	07.1 < 12	59.9	90	40	380.7	542.8	420	Fail
16	100	17.7	09.7 < 12	45.2	50	42	383.1	553.2	420	Fail
16	200	17.7	12.2 > 12	31.1	00	52	387.1	568.4	420	G280

* Most welded bars failed because of the reduced elongations were not conformed to the specification limit.

TABLE VII
TEST RESULTS OF G4, TRANSVERSE REINFORCEMENT

Bar des. No.	No. of cross bars	Yield Strength (MPa)				Ultimate Strength (MPa)				Elongation (%)			
		uw	w	w/uw	r (%)	uw	w	w/uw	r (%)	uw	w	w/uw	r (%)
16	1	447.5	446.5	1.00	0.2	654.0	657.8	1.01	- 0.6	17.7	10.2	0.58	42.4
16	2	447.5	442.6	0.99	1.1	654.0	648.3	0.99	0.9	17.7	10.1	0.57	42.9
16	3	447.5	445.5	1.00	0.5	654.0	651.8	1.00	0.3	17.7	10.3	0.58	41.8

uw: un-welded, w: welded, r: reduction. The (-) sign means that the value has been increased. The transverse bars were spaced 100 mm c/c.

TABLE VIII
TEST RESULTS OF G5, REINFORCEMENT BENDING

Bar des. No.	Test variable	Sample Grade	Inner roller diameter	Hook angle	Result	Failure mode
8	Normal	G550	Ø32 mm	180°	Pass	Perfect bend, No cracks
8	Lap connected	G550	Ø32 mm	180°	Pass	Perfect bend, No cracks
8	Link connected	G550	Ø32 mm	180°	Fail	Bar rupture, weld failure
12	Normal	G550	Ø44 mm	180°	Pass	Perfect bend, No cracks
12	Lap connected	G550	Ø44 mm	180°	Pass	Perfect bend, No cracks
12	Link connected	G550	Ø44 mm	180°	Fail	Bar rupture, weld failure
25	Normal	G420	Ø128 mm	180°	Pass	Perfect bend, No cracks
25	Lap connected	G420	Ø128 mm	180°	Fail	Bar deeply cracked
25	Link connected	G420	Ø128 mm	180°	Fail	Welding bond failure

TABLE IX
TEST RESULTS OF G6, WELD GROOVE SHAPE

Bar des. No.	Weld length mm	Groove shape	Un-welded			Welded			Welded/un-welded			Reduction (%)		
			Yield (MPa)	Ultimate (MPa)	Elongation (%)	Yield (MPa)	Ultimate (MPa)	Elongation (%)	Yield	Ultimate	Elongation	Yield	Ultimate	Elongation
16	32	Square	447.5	654.0	17.7	251.1	317.8	1.6	0.56	0.49	0.09	43.9	51.4	91.0
16	32	Bevel	447.5	654.0	17.7	332.1	388.3	3.5	0.74	0.59	0.20	25.8	40.6	80.2
16	32	Vee	447.5	654.0	17.7	391.9	479.0	5.1	0.88	0.73	0.29	12.4	26.8	71.2

IX. ANALYSIS OF THE TEST RESULTS

Group-1: Normal Tests

In normal test results each data point is the average of three test specimens. All tested parameters are conformed to specifications, except in case of 12 and 25mm bars, the nominal area are less by 5mm^2. Bar deformations can have an important role in welded bars, because height of deformation and ribs will increase the total contact area for bar and welding metal bond strength, whereas during tensile test, such heights will produce points of stress concentration. Therefore the maximum spacing of deformations restricted by specification, as by increasing such points the tensile stress will better distribute over the bar length.

Group-2: Weld metal mechanical properties

In ASD (allowable stress design), the strength of welds is expressed in terms of allowable stress. In LRFD (load and

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resistance factor design), the design strength of welds is taken as the smaller of the design strength of the base material (expressed as a function of the yield stress of the material) and the design strength of the weld electrode (expressed as a function of the strength of the electrode EXX). These allowable stresses and design strengths are summarized in Table X (AISC-LRFD, 2005; Wai and Eric, 2005). During design using ASD, the computed stress in the weld shall not exceed its allowable value. During design using LRFD, the design strength of welds should exceed the required strength obtained by dividing the load to be transmitted by the effective area of the welds (Omer et al., 1999; Franchi, A. and Crespi, P., 2007).

In Table X, the guaranteed allowable stresses from test results are so close to the allowable stresses for smaller bars with a little deviation for Ø25mm, which refers to the non-homogeneous matrix of weld metal particles and for size effects. ACI 318 (2011, pp. 47 & 219) stated that deformed wire larger than Ø16mm is treated as plain wire because tests show that Ø20mm wire will achieve only approximately 60 percent of the bond strength in tension.

TABLE X
ALLOWABLE TENSILE STRESS FOR THE WELDED BARS

Design method	Allowable tensile stress	Ø8 mm	Ø12 mm	Ø25 mm
ASD	0.6fyb	405.2	370.6	331.6
	0.5fub	391.4	371.1	333.6
LRFD	0.9fyb	607.9	555.8	497.4
	0.9fyw	427.9	373.9	285.8
Allowable stress on the welded bars		391.4=0.58fyb	370.6=0.60fyb	285.8=0.52fyb
Guaranteed allowable stress from test results		409.5=0.61fyb	392.1=0.63fyb	280.3=0.51fyb

fyb: bar yield strength, fyw: weld metal yield strength, fub: bar ultimate strength.

The strength of the weld metal varies inversely with cross-sectional area (Shultz and Jackson, 1973), as shown in Fig. 1–a and Fig. 1-b, especially for the yield strength which decrease in a steeper slope. The case is referring to have more weak points in a larger sample. Reducing strength for constant density material means, the material is going to be more ductile, with increased elongation (Fig.1-c). Density of the weld metal is near to 7850 kg/m^3 of reinforcement bars (Fig. 1-d), also for the strength, whereas ductility is much smaller. This smaller original ductility with the heat input effects, will produce a brittle welded reinforcement bars in the welding points (Omer, et al., 1999; Popovic, et al., 2010).

Group-3: Strength and ductility reduction

Theoretically, the strength results for this group reinforcement bars must at least as strong as double of the normal un-welded single bars, if the resistance provided by the additional area of weld is ignored, but it is clear in Table V and Table VI that the strength is decreased. Actually the reduction is caused by the heat input during welding (CRSI, 2004; Wai, and Eric, 2005; AWS A3.0M, 2010; Popovic, et al., 2010), high heat input result in low strength, low hardness and low toughness, whereas low heat input (≤ 60°C) will give risk of hydrogen cracking in the weld (Scott, 1999; Hakansson, 2002).

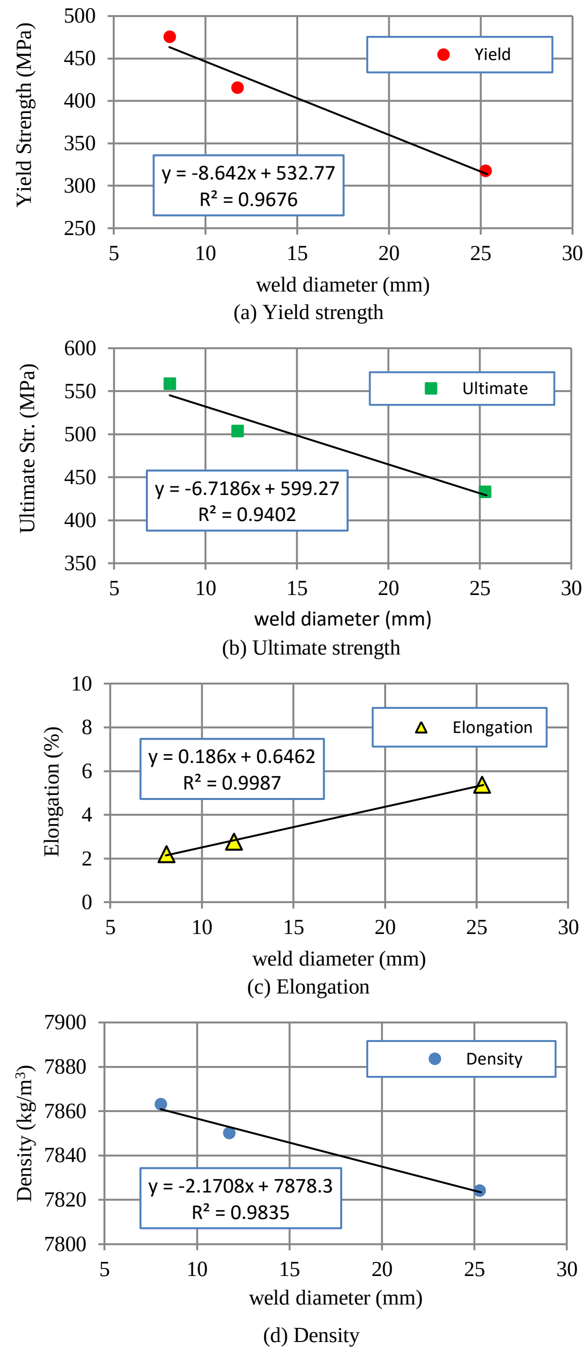


Fig. 1. Results of G2: weld material properties vs. weld diameter

In Fig. 2 the reduction in the yield and ultimate strength is mostly depend on the bar diameter and the welded length. When the bar diameter is less the effects of the welding heat is appeared more which leads to more strength reduction (Popovic, et al. 2010; Achillopoulou, Pardalakis and

Karabinis, 2013). When the welding length is increased there is more heating effects and the strength reduction is more. The reduction ratio in the yield strength is always more than that in the ultimate strength. Research stated 30% reduction in yield and 10% reduction in ultimate strength shall be expected (Scott, 1999).

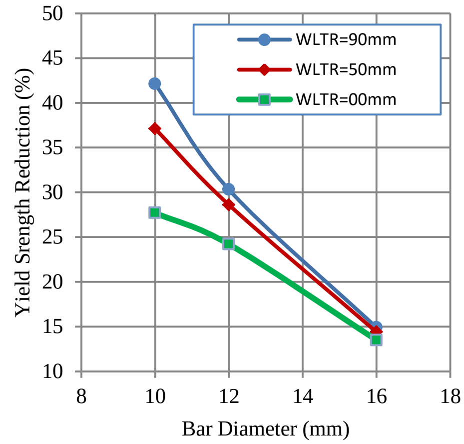
In Fig. 2-c the reduction in the elongation is so large 31-62% (Nikolaou and Papadimitriou, 2004) stated as 50%), in which the remained post weld elongation is no more conformed to the specification limits as shown in Table VI. Reduction in elongation leads to decrease the failure time from yield point until the ultimate strength and then failure, so the plastic range safety is decreased and sudden failures should be expected.

The mentioned welding heat effects will gradually reduce when the bar diameters are of larger sizes, when the bar diameter is larger the generated welding weakening heat can't penetrate to the core of the bar like the smaller bars. This fact can be seen in the failure section as in the smaller bars (like 10 mm) the boundary between the bars' surface and the welding can't be separated, whereas in the larger bars (like 16 mm) the separation line can be seen easily, in more simple words, the welding heat input caused re-crystallization of the particles for smaller bar diameters (Omer, et al., 1999; Popovic, et al., 2010).

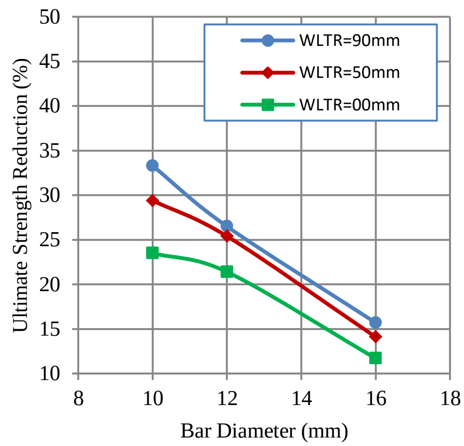
Group-4: Transverse bars

Welding of crossing reinforcing bars can lead to local embrittlement of the steel (ACI 318, 2011; AWS D1.4M, 2011) and during tension test the bar will rupture in the point directly to the edge of welding. The inputted heat of welding is the cause for this local weakening (Hakansson, 2002; CRSI, 2004; Nurnberger, 2005). For the same reason ACI 318 (2011, pp. 219) had not permitted reduction in welded development length and welded splice, when a cross bar exist less than 50mm from critical section. This case is different from cold welding for deformed welded wire meshes or mats manufactured in mill that has not considerable changes in properties caused by welding (ASTM A184M, 2005; ACI 318, 2011).

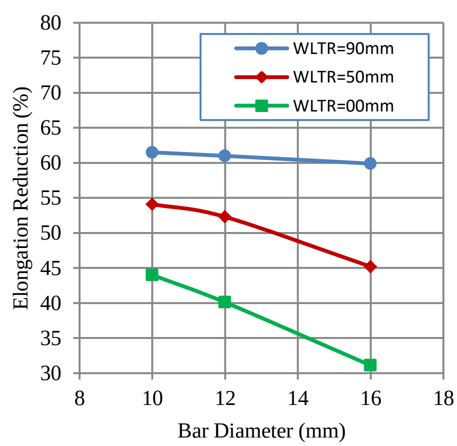
The term "tack welding" has become firmly established and embedded in building codes and in design and construction specifications to describe the connection of crossing bars by small arc welds (CRSI, 2004). Tack welding can seriously weaken a bar at the point welded by creating a metallurgical notch effect. This operation can be performed safely only when the material welded and welding operations are under continuous competent control, as in the manufacture of welded wire reinforcement (Omer, et al., 1999; Serna, et al., 2002; Nikolaou and Papadimitriou, 2004; ACI 318, 2011). During preparation of test samples in this group, the welding was well controlled considering (continuous competent control); therefore the test results shown in Table VII and Fig. 3 are of negligible reduction in yield and ultimate strengths. The reduction in ductility was around 40% of original elongation, but the retained elongation (10%) is still conformed to specification requirements (9% min.).



(a) Yield strength



(b) Ultimate strength



(c) Elongation

Fig. 2. Results G3: reduction s vs. different bar diameters for different WLTR (weld length in tension range, between grips).

The test simulation is different from reaction of transverse bars during loading in a real structure, because there is already stresses in the cross bars and it is required complex procedure to consider three dimensional stress analyses. But the purpose of the investigation is determining pure effects of the welding due to the tack welds and to avoid interference of stresses in the cross bars. In the other side tests demonstrate that cross

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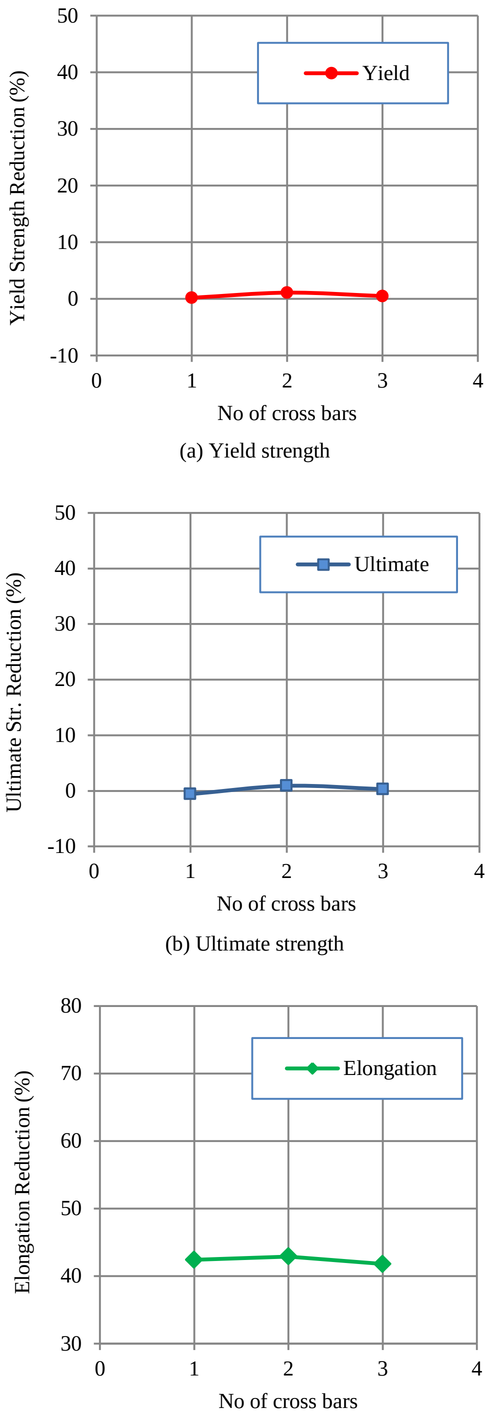
reinforcement rarely yields during a bond failure (ACI 318, 2011, pp.211).



(a) Yield strength

(b) Ultimate strength

(c) Elongation

Fig. 3. Results of Group 4: No of cross bars vs. reduced parameters

Group-5: Bending of reinforcement

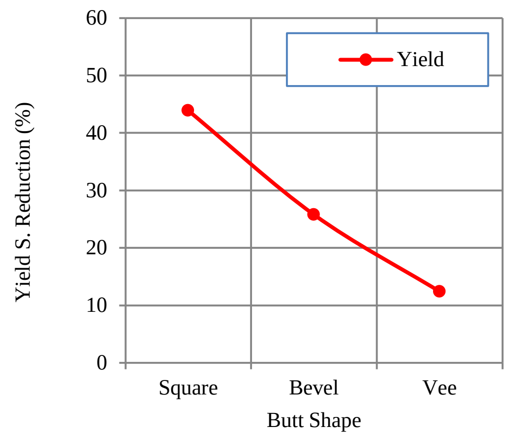
The results of this group are shown in Table VIII, normal bars were passed perfectly from the test without local angles and visible surface cracks; whereas the lapped welded bars can't resist relatively large bending load in case of 25mm diameter bars, the case was different for small diameters (like 8 and 12mm) as they were passed from the test. In case of linked welded bars all the bars were failed to bend, because of the un-connected main bars together, so the critical point was at the center of the bar, therefore the high stresses leads to bond failure between weld. In fact the outer part from neutral axis of the bar was subjected to tensile stress, which is directly related to the elongation limits of the bars. Whereas the reduced elongations due to the heat of welding (shown in Table VI, VII and IX, will not permit the outer surface of the bar to extend like the un-welded bars, this will cause the rupture of the bars and welding, and then a brittle failure was happened (Serna, et al., 2002).

Welded wire reinforcement can be used for stirrups and ties. The wire at welded intersections does not have the same uniform ductility and bendability as in areas that were not heated. These effects of the welding temperature are usually dissipated in a distance of approximately four bar diameters (ACI 318, 2011) or the effect may extend to 100mm from the weld toe (AWS A3.0M, 2010). Tests have shown that ASTM-A615 G280 & G420 reinforcing bars can be cold bent and straightened up to 90 degrees at or near the minimum diameter. If cracking or breakage is encountered, heating to maximum temperature of 820°C may avoid this condition for the remainder of the bars (ACI 318, 2011, pp.90).

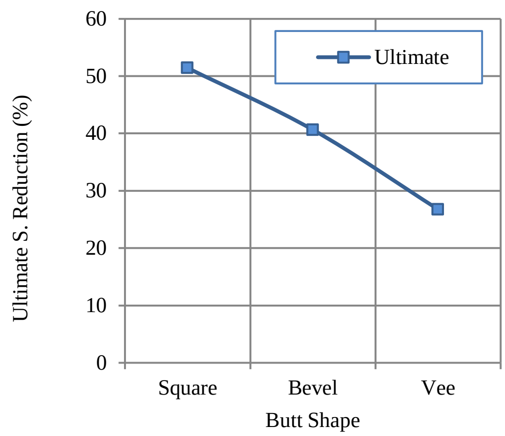
Group-6: Weld groove shape

Welded connections are connections whose components are joined together primarily by welds. Welds can be classified according to: the types of welds (groove welds, fillet welds, plug welds, and slot welds), the positions of the welds (horizontal welds, vertical welds, overhead welds, and flat welds) and the types of joints (butt, lap, corner, edge, and tee) (Omer, et al., 1999; AISC, 2005; Wai, and Eric, 2005).
The test results of this group are shown in Table IX and Fig. 4, by noting the strength of the groove shapes, easily it can be concluded that the V-shaped groove will be the most strong type, and the state may be justified by the principle of: the larger contacted surface between the bar and weld metal, gives larger effective bonding area, thus stronger bond had been produced.

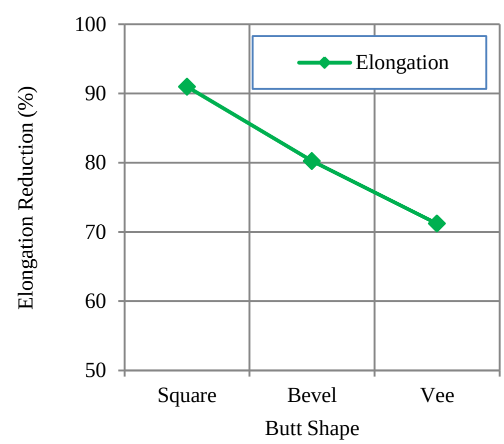
The groove welds chosen were used in welding of an informal construction projects, and their strength may be still in the range of permitted levels by AISC code (2005) for low stress level not exceeding 0.5fy especially for V-shape. Whereas these types of welding shall be completely avoided for alterations in reinforced concrete using SMAW welding, for quality works (Lincoln E., 2014), because of the brittle joints, which leads to sudden rupture of the bars or welds, may be before appearing visible cracks in concrete (Choi, et al., 2013). The reason is the reduction in elongation of the joint; other welding methods like flash butt pressure welding or robot welder showed accepted results (Hakansson, 2002; Nurnberger, 2005; Chvertko, Skachkov and Chvertko, 2011).



(a) Yield strength



(b) Ultimate strength



(c) Elongation

Fig. 4. Results of Group 6: weld groove shape (parallel to tensile force) vs. reduced parameters.

Although fillet welds are generally weaker than groove welds, they are used more often because they allow for larger tolerances during erection than groove welds. Groove welds are expensive to make and they do not provide much reliability in transmitting tensile stresses perpendicular to the faying surfaces. Furthermore, quality control of such welds is difficult because inspection of the welds is rather arduous (Omer, et al., 1999; Wai and Eric, 2005). As a result it is recommended to connect reinforcement bars using fillet weld to have horizontal or overhead welding positions with edge, lap or linked lap joints with cross-sections shaped V-flare perpendicular to tensile force (Bohler, 2005).

X. Failure Planes and Explanatory Images

Images shown in Fig. 5 can explain more aspects of welding heat input, failure sections and critical points during the tensile test and the bending tests.

XI. Conclusions

1) The strength of welding metal is directly related to the size of weld bead and thickness, increasing welding area 2 and 10 times, the yield strength will decrease 13% and 33%, respectively. Weld metal density is same as for carbon steel bars about 7850 kg/m^3.
2) The strength and elongation of the welded base metal decreased by (10-40%) and (30-60%) respectively, depending on the weld size. To avoid catastrophic failure in concrete structures, the stress level in welded bars shall not exceed 0.5f_y of the bars.
3) Technical welding of transverse bars has negligible effects in strength of the bars, whereas it should be determined that precautions regards to ductility are in order, as elongation may reduce by 40%. Therefore, reducing the heat input to the minimum allowable is preferred.
4) Cold bending of the welded bars shall be prevented especially for bar diameters of 16mm or more, or else the bar shall be heated at least to 160°C prior to bending.
5) Groove welds shall be prevented, as these types of welds will not provide the required elongation which will reduce by (70-90%), therefore groove welds will fail more likely as brittle materials than ductile steel bars.

XII. Recommendations

1) Welding may be required in many cases in reinforced concrete construction, therefore it is important for designers and site engineers to have comprehensive information about metallurgical changes of base metal caused by welding.
2) Technical welding (which is not common in Kurdistan) shall be performed by professional welder or expert welders for critical locations; under continuous competent control. It shall be inspected and tested, before casting of the surround concrete.
3) It is recommended to connect reinforcing bars using fillet weld to have flat and overhead welding positions with edge, lap or linked lap joints with cross-sections shaped V-flare perpendicular to tensile force direction.

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Test bars 25/16/12/10/8mm


Heat input during welding


Bars Measuring's


Welding Electrodes E6013


Prepared Bars (all)


Fillet weld, V-flare lap joint


Failures of G2 25mm bars


Failures of G2, 8,12,25mm


Failure of a specimen in G3


Failure sections in G3


Prepared bars G4

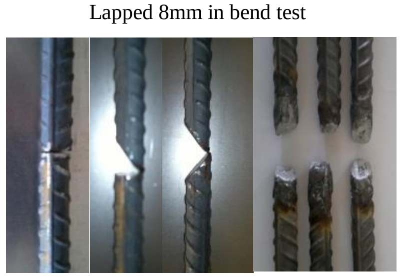

Failure planes for G4


Prepared for bending


Lapped 8mm in bend test


pass/fail specimens-bend test


Crack/bond failure in bend test


Prepared/failure bars in G6


Tensile testing machine

Fig. 5. Failure of specimens and explanatory images

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