PORT SAID ENGINEERING RESEARCH JOURNAL
Faculty of Engineering – Port Said University
Volume (20) No. 2 September 2016 pp: 124:131

Evaluation of Mixed Structural Steel lap Joints Using Experimental and Finite Element Methods

Prof. Dr. Ebtisam F. Abdel-Gwad [1], Dr. Ahmed Abdel Rahman Elkaseer [2],
Dr. Mohamed Saber [3] and [4] Eng. Mahmoud Samy Elqazzaz

ABSTRACT

Connections in engineering structures such as aircraft, marine and automotive should be designed to fulfill the intended level of safety, serviceability, durability, and the ability to withstand the stresses applied on global structures. Most structures use a single connecting method such as mechanical fasteners (bolt- rivets), bonding and welding to make the connection between adjoining members. However, it is sometimes necessary to mix different joining methods in a single connection, or to replace some joints by higher strength joining elements in order to increase the capacity of an existing joint. To enable mixed joints between mechanical fasteners and welds to become a strengthening viable joining technology in industry, the present study aims to develop a better understanding for mechanical behavior of mixed joints of an overlap steel plates experimentally using the static tension test and with finite element method, either connected with single or mixed joining elements. The investigation includes a basic single joint of double fillet welds steel lap plates. Four mixed joining methods are evaluated including a combination of the basic single joint with a rivet, a bolt, an arc spot penetrate weld and a plug weld. Experimental results for static tension tests conducted at room temperature are presented and considered to be the most reliable datum line. Mixed joining techniques resulted in strengthening the basic steel structure lap joint. Also, the finite element model(FEM) which is time consuming but inexpensive was carried out to predict detailed stress-extension distributions within these joints and also to predict tensile behavior of the basic purely single joint and when mixing with other joining configurations. A comparison of finite element analysis is conducted with experimental results and the results are validated. Finite element models showed a good agreement with the experimental results. Therefore, the models procedures seem adequate for assessing stress level for use in evaluating both single and mixed joints.

Keywords: Mechanical fasteners, Fusion welding, Mixed joints, Tensile behavior, Finite Element Analysis (FEA)

1. INTRODUCTION

Mechanical fasteners and welding are the preferred methods to assemble structural components. Bolts are used for cases where removable sections are required. Their main advantage over other techniques is that it is easy to disassemble the structure, which facilitates maintenance and allows for replacement of damaged parts beside their strength, reusability and appearance. Rivets and welding are used for permanent joints. Most structural components use a purely single joining technique to connect members together and provide the means of transferring loads between components acting on them. Many single joining methods are available and applied in structures assembly and evaluated experimentally or using FEM [1-2]. Accordingly, the mechanical behavior of some single joints are shown in Fig.1.

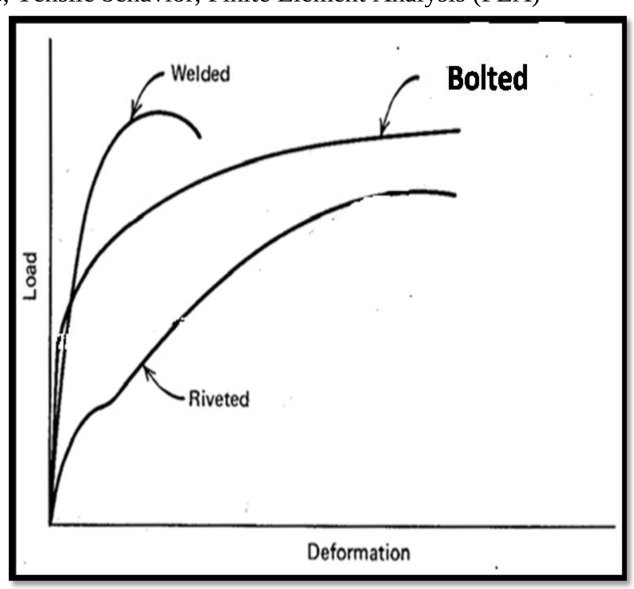

Fig. (1) Load - deformation relationships for different joining methods [1]

[1,2,3] *Dept. of Production Eng. and Mech. Design, Faculty of Eng., Port-Said Uni., Egypt.*
[4] *Industrial Developed School, Elmenzala, Egypt.*

Safe performance makes it necessary to combine different joining methods in a mixed joint for a single structure to share the applied load. A mixed joint is a joint that utilizes two different types of joining methods. Addition of other joining methods help to provide some strength to the original joint and allow the structure to carry larger loads or improve performance. It is easy to add welds to a joint after it has been first bolted or riveted into place. Mixed joints of this type have a wide application for reinforcement of existing mechanically fastened joints. The main role also is safety when the main joint fails, so the additional joining method could keep joined structure in place for an additional period of time preventing a catastrophic failure [3].

In other situations, necessary space may not be available for installing multi mechanical fasteners, so adding welds or replacing several rivets with a high-strength bolt may be the solution for strengthening the existing joint and overcome assembly problems. Joints of this type are generally referred to as combination joints, hybrid joints or mixed joints. Common mixed joint techniques shown in Fig. 2 involve combination of mechanical fasteners (bolts with rivets), combination of welding process with mechanical fasteners (arc weld with bolts), combination of welding processes (laser with tungsten inert gas-TIG), combination of adhesive bonding with welding process (adhesive with plasma or adhesive bonding with spot-welding) and combination of adhesive bonding with mechanical fasteners (adhesive with bolts) [4 - 9].

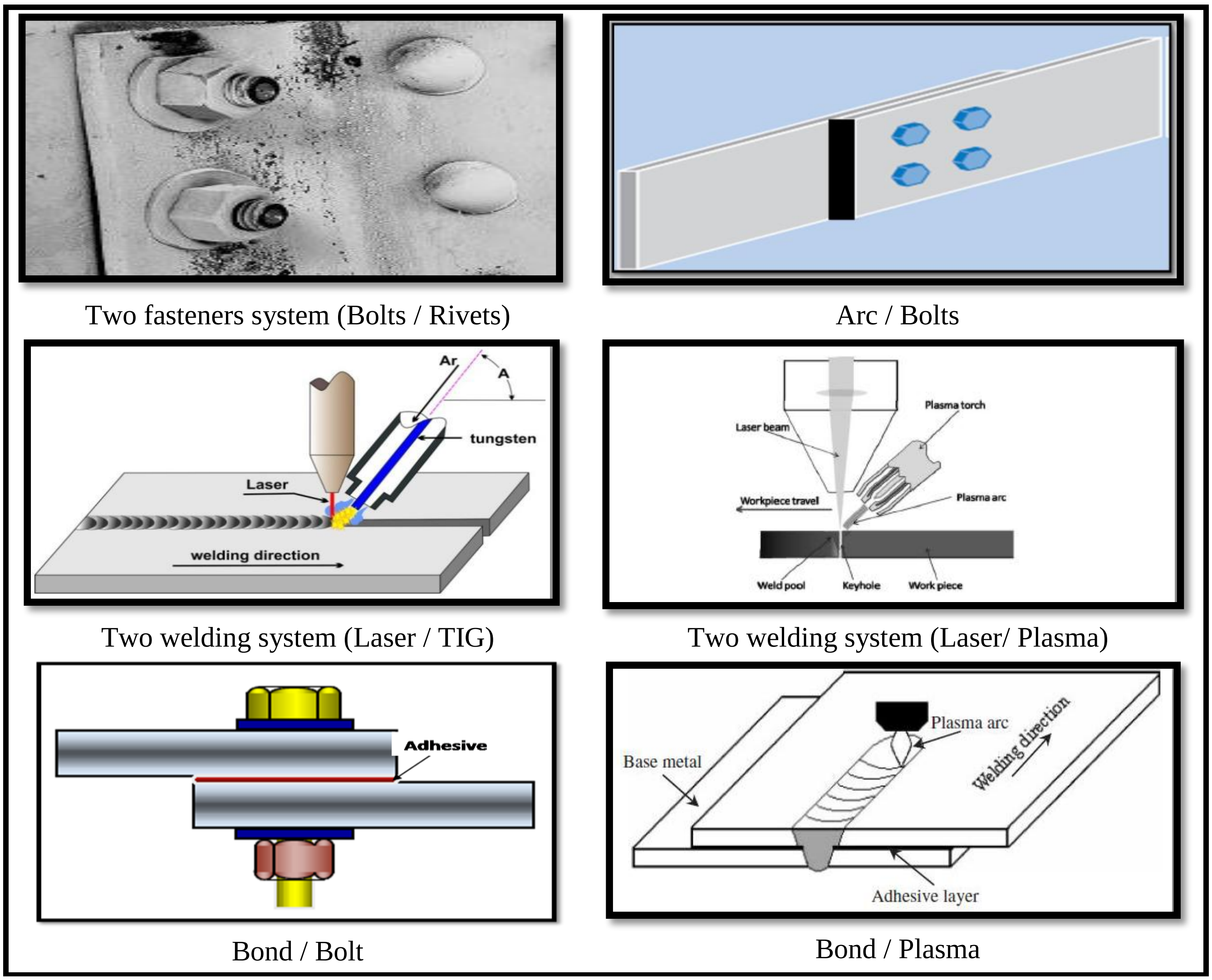

Fig. (2) Common mixed joint techniques [1 and 5-7]

The behavior of mixed joints with some joining combinations has been studied before and proved that the failure loads has been improved compared to purely separated joints [10-11].

Present Testing program have been performed to evaluate validity of a variety of joining techniques including bolts, rivets, spot arc penetrate welds and plug welds mixed with the basic single joint of double fillet welds steel lap plates for strengthening it experimentally and using (3D-Abaqus software) finite element method.

2. EXPERIMENTAL PROCEDURES

2.1 Materials and Joint Description

The samples in the present experimental program were designed for explaining the effect of each separate joining technique included riveting, bolting, welding (either Arc penetrate weld or plug weld) when mixed with double fillet welds lap joint (double fillet welds plus a bolt, plus a rivet, plus a penetrate weld and plus a plug weld) on their tensile behavior.

Present study covers 33 test plates of low carbon steel with geometric description shown in Fig. 3 A. Lap joint with the recommended lap distance of 50 mm was chosen, in which minimum lap distance shall not be less than 5 times the smaller thickness of the parts to be joined. Configuration of the lap joint is also shown in Fig. 3 B.

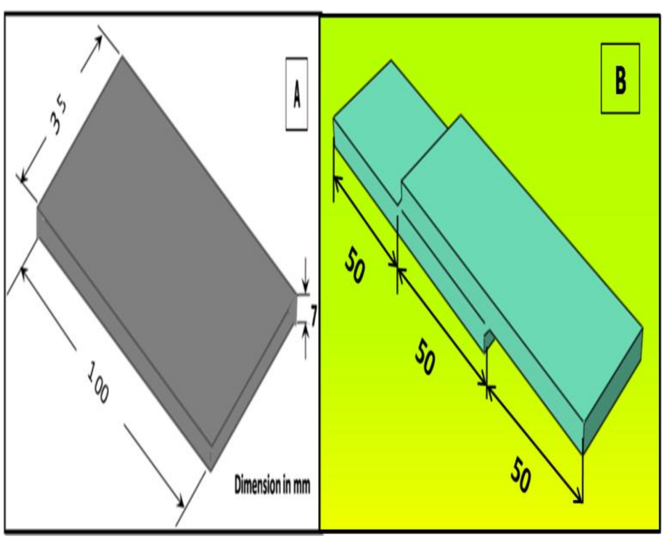

Fig.(3) Configuration of test plate and lap joint

Chemical composition using the spectrum analysis of the base plate, weld, bolt and rivet metals are given in Table 1

Table (1): Chemical composition of used materials

element %	C	Mn	Si	S	P	Cr	Ni	Al	Cu	Fe
base metal	0.15	0.46	0.02	0.01	0.02	0.03	0.02	0.04	0.03	Bal
weld metal	≤0.12	0.3-0.6	≤0.35	≤0.04	≤0.04					Bal
bolt metal	0.17	0.73	0.17	0.01	0.02	0.15	0.02	0.01	0.01	Bal
rivet metal	0.12	0.51	0.13	0.01	0.01	0.02	0.03	0.01	0.03	Bal

2.2 Joining Procedures

2.2.1 Basic single joint (double fillet welds)

Double fillet welds in present investigation were applied on all 33 lap joints as a basic joining method using the manual arc welding with electrode specification: AWS A5.1 E 6013, diameter 3.2 mm, current 100A and voltage 25V.Configuration of the welded joint is shown in Fig.4

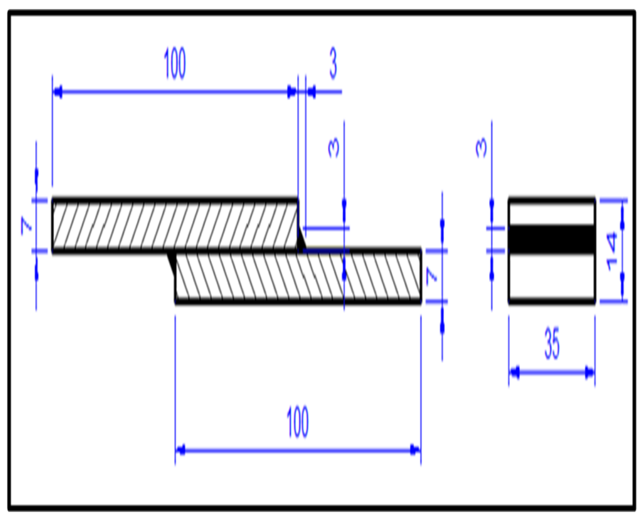

Fig. (4) Configuration of the double fillet welds single lap joint

2.2.2 Mixed joints

a. <u>A bolt / double fillet welds</u>

Identical bolt - nut - washer components used in mixed joints are shown in Fig. 5. Diameter of the bolt is 10 mm and the threads is chosen to be located at shear plane at lap joint interfaces because capacity of a bolt is greater with the threads located out the shear plan. Bolts are installed to meet snug off condition using a wrench [12]. Chemical composition of bolts material is illustrated in Table 1.

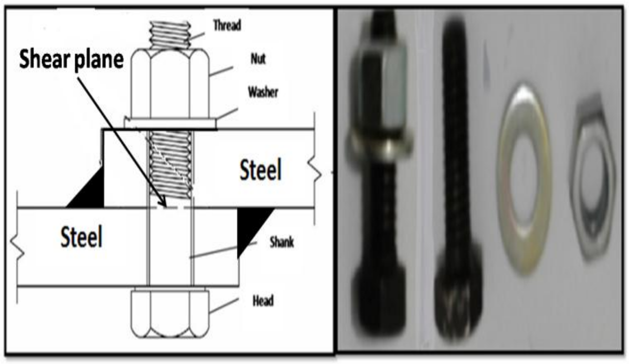

Fig. (5) Bolt/double fillet welds mixed joint

b. **A rivet / double fillet welds**

Button head steel rivet of 10 mm shank diameter was chosen and hot riveted with the double fillet welds joint as shown in Fig.6. The rivet is heated to bright red, placed in its hole and held firmly in position while hammering and shaping the shank end. Hot riveting was chosen to produce high clamping force because the rivet shortens as it cools. The chemical composition of rivet material is illustrated in Table1

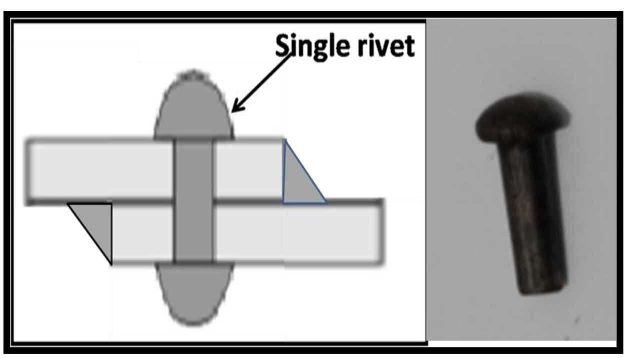

Fig. (6) Rivet /double fillet welds mixed joint

c. **An arc spot penetrate weld / double fillet welds**

Same manual arc welding process, electrode and setting parameters were also used to add a single arc spot penetrate weld to the basic double fillet welds specimen by filling hole of 10mm diameter and 14 mm length. The finished result revealed a circular shape; full penetrate spot weld as shown in Fig. 7.

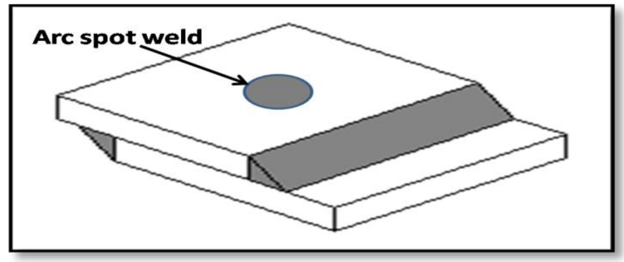

Fig. (7) Arc spot penetrate weld / double fillet welds mixed joint

d. **A plug weld / double fillet welds**

A plug weld was added to the basic double fillet welds specimen. A hole of 10mm diameter was drilled only into the 7mm top piece thickness, then it is laid over the bottom one. A weld was made by running a bead inside of the drilled hole. The finished result revealed a circular shape, un burn through spot weld as shown in Fig. 8

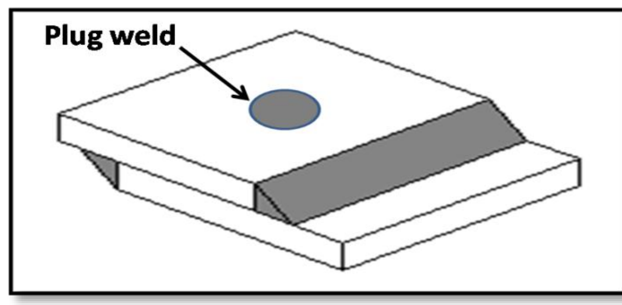

Fig. (8) A plug weld / double fillet welds mixed joint

2.3 Tensile Testing

A tensile testing machine-German KB pruftechnik GmbH (Model UP 9709).of - 60 tons capacity has been used for room temperature tension testing of the base metal, single joint and mixed joints at a crosshead speed of 10 mm/min. Stress extension data recorded directly by the attached computer.

2.4 Finite Element Method

The finite element method (FEM) is a numerical procedure used in present work to confirm the experimental results in the elastic state. Also it is claimed to predict the best mixed joining method of the overlap steel samples. The commercial package ABAQUS explicit software was designed and applied to direct the simulation of the tensile stress at the single and mixed joints. Necessary steps were completed inside the software established on the jointing techniques. Three dimensions finite element type: QUAD8- C3D8R-solid, was chosen for both plate and weld region during all investigated joints. Characteristic properties of the used steel are shown in Table 2.

Table 2 Characteristic properties of the applied steel

Density	7850 kg/m^3
Elastic stress	520 MPa
Modulus of elasticity	210 GPa
Poisson's Ratio	0.3

Shape, size of mish, and boundary condition (loading direction and fixation) are identified in Fig.9.

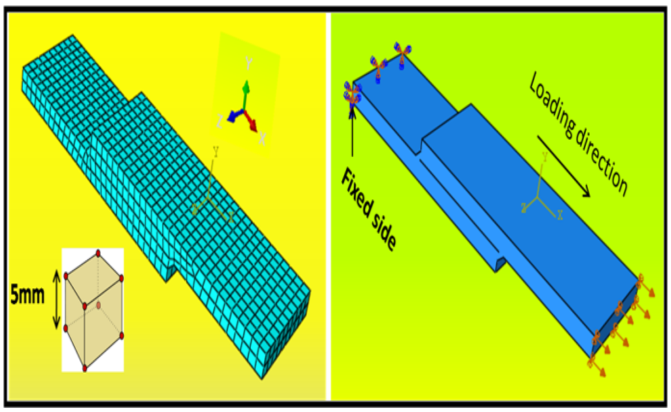

Fig. (9) FE model, mish and boundary conditions

Elastic displacements of 4.5, 1.0, 2.4, 1.8, 1.6, 1.4 mm during tensile of base plate, basic single double fillet welds lap joint, a rivet mixed with the basic single lap joint, a bolt mixed with the basic single lap joint, an arc spot penetrate weld mixed with the basic single lap joint, and a plug weld mixed with the basic single lap joint respectively were fed into software in the loading direction-x.

3. RESULTS and DISCUSSION

3.1 Experimental Results

3.1.1 Failure modes of mixed joints

Failure of single and mixed joints is shown in Fig. 10. A complete interface separation in the basic single joint is observed for the overlap plates at the shear planes of fillet welds. All investigated mixed joints revealed a shear fracture at mixed region at the rivet, bolt, spot arc penetrate weld and plug weld, besides the fracture at the shear planes of fillet welds of basic joint.

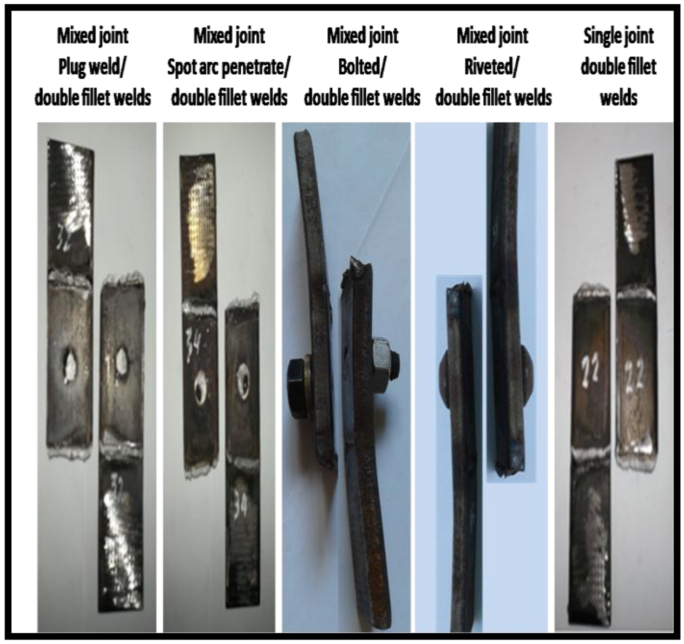

Fig. 10 Failure mode of single and mixed joints

3.1.2 Strengthening at Elastic Region

Experimental results in Fig. 11, indicate a higher level of elastic stress Ϭe at each of a single rivet, a single bolt, an arc spot penetrate weld and a plug weld when mixed with the basic double fillet welds steel lap joint. Mixed joint with one rivet, record the highest strengthening level approximated to 60% Ϭe compared with the basic single joint. Lower strengthening levels approximated to 30%, 27% and 16% Ϭe are recorded for mixed joints with each of one bolt, one spot arc penetrate weld and one plug weld when compared respectively with the basic single joint of double fillet welds lap joint.

3.1.3 Strengthening at Plastic Region

A higher level of ultimate stress Ϭu is indicated also in Fig. 11 at each of a single rivet, a single bolt, an arc spot penetrate weld and a plug weld when mixed with the basic double fillet welds steel lap joint. Mixed joint with one rivet, recorded the highest strengthening level approximated to 46% Ϭu compared with the basic single joint. Also lower strengthening levels within the plastic region, approximated to 27.5%, 24% and 17.5% Ϭu were recorded for each of one spot arc penetrate weld, one plug weld and one bolt when mixed respectively with the basic single joint of double fillet welds lap joint. So, Mechanical fasteners rivet or bolt seemed to be better strengthening elements within the elastic zone than the welds (arc spot penetrate or plug) while either mechanical fastener (rivet) or a weld (one arc spot penetrate weld) seemed to be better strengthening elements within the plastic zone.

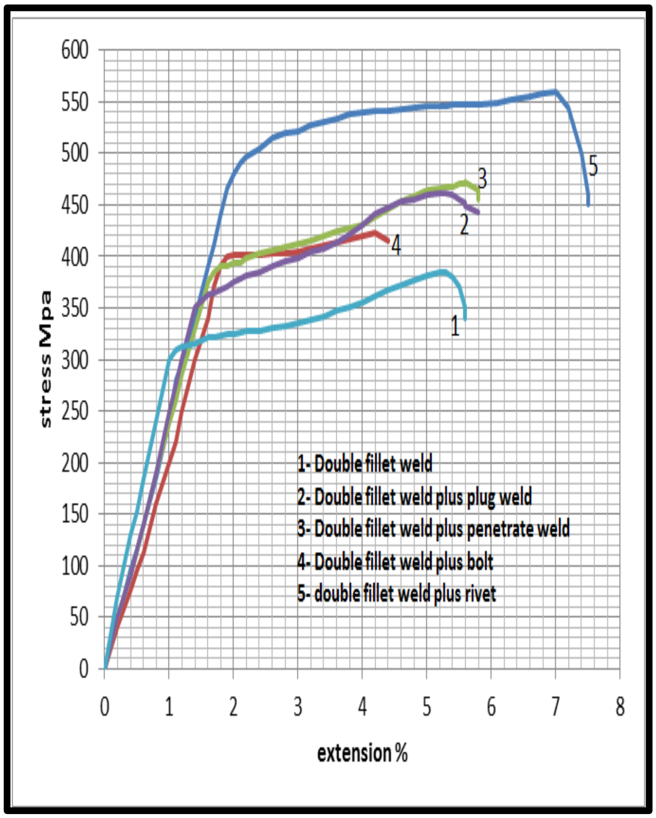

Fig. (11) Experimental stress extension curves for single and mixed joints

3.2 Finite Element Result and Validation

The finite element results within elastic region clarified the elastic stress distribution for all investigated joints. Also the FE results and the experimental results were compared and evaluated.

a. <u>Single Joint:</u>

In case of the basic single joint (double fillet welds), stress distribution within elastic region is shown in Fig. 12. Maximum elastic stress predicted from the present modeling 388 MPa is in acceptable agreement with present experimental measurement of 300 MPa.

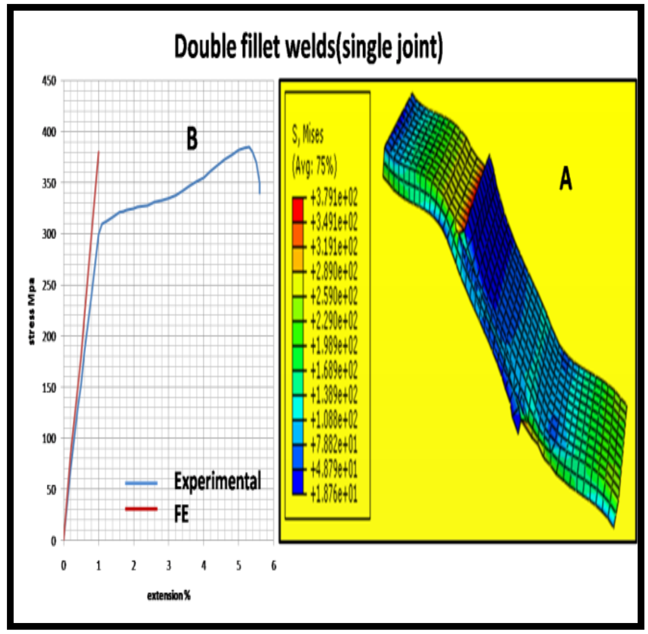

Fig. (12) Single joint (double fillet welds):
A) 3D elastic stress field
B) Experimental and numerical elastic stress

b. <u>Mixed joints:</u>

For each of the mixed joints : one rivet, one bolt, one spot weld and one plug weld, mixed with the single joint of double fillet welds respectively, the 3D stress field distribution (A) within elastic region and also the elastic stress either numerical or tested (B) are shown in Fig. 13 a, b, c and d respectively.

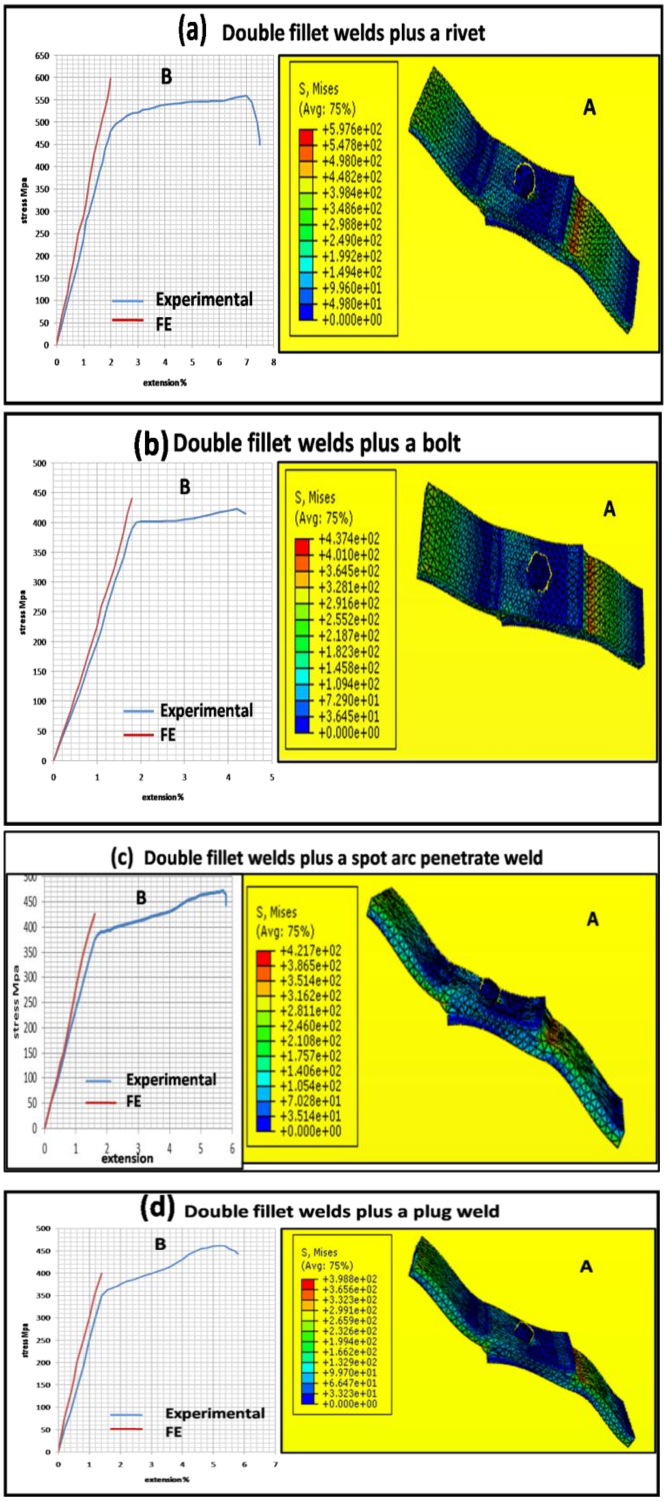

Fig. (13) Mixed joints:
A) 3D elastic stress field
B) Experimental and numerical elastic stress

The stress distribution indicated maximum elastic stress value at the fillet welds for each investigated mixed joint. Presence of each strengthening element in the mixed joints seems to increase resistance of the basic single joint to the applied load. The proposed elastic criteria predicted maximum elastic stress for all the mixed joints higher than that of the single joint within elastic region (Figs.12 to 13).

The obtained numerical results of elastic stress of mixed joints were compared with the present experimental data. The predicted elastic stresses of mixed joints were 598, 438.5, 422 and 399 MPa compared with the present experimental measurements of 480, 390, 380 and 347 MPa (for the double fillet welds when mixed with each of one rivet, one bolt, one arc spot penetrate weld and one plug weld respectively).

An acceptable agreement between numerical prediction and measured data was found. Present model can be examined later to be applied in 3d stress field till failure of the joints.

CONCLUSIONS

Present approach to investigate the strengthening effect of a number of mixed joints compared to a single joint has been carried out. Based on the obtained experimental and predicted results the following conclusions can be drawn:

- The basic single double fillet welds steel overlap joint, mixed with other joining methods either mechanical fasteners or fusion welds improve and strengthen the basic joint.
- The basic single joint exhibits earlier failures than the states when other joining methods are added.
- Additional strengthening at elastic region- $Ϭe$ approximated to 60%, 30%, 27% and 16% are achieved when mixing a rivet, a bolt, a spot arc penetrate weld and a plug weld respectively to the basic single joint.
- Additional strengthening at plastic region- $Ϭu$ approximated to 46%, 27.5%, 24% and 17.5% are achieved when mixing a rivet, a bolt, a spot arc penetrate weld and a plug weld respectively to the basic single joint.
- Type of joining elements added to the basic joint is the key factor that must be considered when determining the extent of load sharing in mixed joints.

- The commercial package ABAQUS applying 3D finite element numerical procedures is an effective tool in prediction of the positive strengthening effect of mixing joints instead of a single joint with a good agreement regarding the experimental results.

REFERENCES

[1] Geoffrey L. Kulak, John W. Fisher, John H. A. Struik : Guide to Design Criteria for Bolted and Riveted Joints, Research Council on Structural Connections, USA (2001)

[2] Alvaro .O and Carlos. S : On the prediction of bolted single-lap composite joints, Department of Continuum Mechanics and Structural Analysis, University Carlos III of Madrid, Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain (2012).

[3] Wang, Peng Hao, "The Effects of Adding Attachments in Conventional Composite Hybrid Joints on Tensile Strength" College of Technology Directed Projects (2010).
http://docs.lib.purdue.edu/techdirproj/29

[4] Campilho, R. D. S. G.; Banea, M. D.; Da Silva: Comparative evaluation of bonded, welded and weld bonded structural joints, Welding Equipment and Technology, Vol. 22 (2011)

[5] EAA Aluminum Automotive Manual – Joining, ©European Aluminum Association (auto@eaa.be) 1, Version (2015)

[6] T. Subramani, R. Senthil Kumar : Modeling and Analysis of Hybrid Composite Joint Using Fem in ANSYS, International Journal Of Modern Engineering Research, Vol. 4 , June (2014)

[7] Duane K. Miller : “Mixing welds and bolts”, Part 1, Welding innovation Vol. XVIII, No. 2 (2001)

[8] Kemal Aldas, Faruk Sen : “Stress analysis of hybrid joints of metal and composite plates via 3D-FEM”, Indian journal of Engineering &Material Sciences, Vol. 20, April (2013)

[9] Geoffrey L. Kulak and Gilberty. Grondin: “ Strength of Joints that Combine Bolts and Welds”, Engineering Journal / Second Quarter (2003)

[10] N. M. Holtz and 0. L. Kulak: “High Strength Bolts and Welds in Load-Sharing systems”,
Department of Civil Engineering, Nova Scotia Technical College, Halifax, Nova Scotia (1970)

[11] Paroissien Eric, Sartor Marc, Huet Jacques: Advances in Integrated Design and Manufacturing in Mechanical Engineering II : Hybrid (Bolted/Bonded) Joints Applied To Aeronautic arts”, Springer Netherlands (2007)

[12] Geoffrey Kulak: High Strength Bolts-A Primer for Structural Engineers, American Institute of Steel Construction, Inc. October (2003).