CAE Modelling of Ultrasonic weld joints used in joining of Plastic parts of Automotive Door trim

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Abstract*— The paper explains the CAE modelling of ultrasonic weld joints used in joining the plastic parts of automotive. The basic of weld procedure are illustrated along with design guidelines. In ultrasonic welding, high-frequency vibrations are applied to two parts or layers of material by a vibrating tool, commonly called a "horn or sonotrode". Welding occurs as the result of heat generated at the interface between the parts or surfaces. This technique is fast, efficient, non-contaminating and requires no consumables. In addition to welding, ultrasonic processes can be used to insert, stake, stud weld and spot weld thermoplastics as well as seal, slit, and laminate thermoplastic films and fabrics. Ultrasonic components can be easily integrated into automated systems. The data presented shows that FEM can be used to analyze physical behavior of ultrasonic weld joint. Some important findings are; the methodology proposed for modelling of weld is highly useful for preparing FE model for static and crash analysis, the information given on thickness of parts is important consideration in design of part, with the discussed post processing method, weld failure can be predicted; redesigning of weld is possible without testing of physical prototype.

***Keywords*— Ultrasonic weld Joint, FE modelling, Forces in ultrasonic weld, Weld failure, Plink, Spotweld**

I. INTRODUCTION

Practical application of ultrasonic welding for rigid plastics was completed in the 1960s. At this point only hard plastics could be welded. The patent for the ultrasonic method for welding rigid thermoplastic parts was awarded to Robert Soloff and Seymour Linsley in 1965. Soloff, the founder of Sonics & Materials Inc., was a lab manager at Branson Instruments where thin plastic films were welded into bags and tubes using ultrasonic probes. He unintentionally moved the probe close to a plastic tape dispenser and the halves of the dispenser welded together. He realized that the probe did not need to be manually moved around the part but that the ultrasonic energy could travel through and around rigid plastics and weld an entire joint. He went on to develop the first ultrasonic press. The first application of this new technology was in the toy industry.

The first car made entirely out of plastic was assembled using ultrasonic welding in 1969.Even though plastic cars did not catch on, ultrasonic welding did. The automotive industry has used it regularly since the 1980s. It is now used for a multitude of applications.

In ultrasonic welding, high-frequency vibrations are applied to two parts or layers of material by a vibrating tool, commonly called a "horn or sonotrode." Welding occurs as the result of heat generated at the interface between the parts or surfaces. This technique is fast, efficient, non-contaminating and requires no consumables. In addition to welding, ultrasonic processes can be used to insert, stake, stud weld and spot weld thermoplastics as well as seal, slit, and laminate thermoplastic films and fabrics. Ultrasonic components can be easily integrated into automated systems.

II. CATEGORIES OF PLASTIC AND ULTRASONIC WELDING PROCESS FOR PLASTIC

A. Categories of Plastic:

The Plastics are generally divided into two categories, which are "thermosets" and "thermoplastics." A thermoset is a plastic in which a chemical reaction sets the molecular bonds after first forming the plastic, and then the bonds cannot be broken again without degrading the plastic. Thermosets cannot be melted; therefore, once a thermoset has set it is impossible to weld it. Examples of thermosets include epoxies, silicone, vulcanized rubber, polyester, and polyurethane.

Thermoplastics, by contrast, form long molecular chains, which are often coiled or intertwined, forming an amorphous structure without any long-range, crystalline order. Some thermoplastics may be fully amorphous, while others have a partially crystalline/partially amorphous structure. Both amorphous and semicrystalline thermoplastics have a glass transition, above which welding can occur, but semicrystallines also have a specific melting point which is above the glass transition. Above this melting point, the viscous liquid will become a free-flowing liquid. Examples of thermoplatics include polyethylene, polypropylene, polyvinylchloride and fluoroplastics like Teflon and Spectralon.

B. Ultrasonic Welding:

Ultrasonic Welding is a plastic welding process, in which two work pieces are bonded as a result of a pressure exerted to the welded parts combined with application of high frequency acoustic vibration.

Ultrasonic vibration transmitted by a metal tool causes oscillating flexing of the material and friction between the parts, which results in a closer contact between the two surfaces with simultaneous local heating of the contact area. The plastic melts in the contact area, the polymer molecules are cross-linked, forming a strong joint.

Ultrasonic Welding cycle takes about 1 sec. The frequency of acoustic vibrations is in the range 20 to 70 kHz. The amplitude of the acoustic vibrations is about 0.002" (0.05 mm).Thickness of the welded parts is limited by the power of the ultrasonic generator.

For joining complex injection molded thermoplastic parts, ultrasonic welding equipment can be easily customized to fit the exact specifications of the parts being welded. The parts are sandwiched between a fixed shaped nest (anvil) and a sonotrode (horn) connected to a transducer, and a ~20 kHz low-amplitude acoustic vibration is emitted. Common frequencies used in ultrasonic welding of thermoplastics are 15 kHz, 20 kHz, 30 kHz, 35 kHz, 40 kHz and 70 kHz. When welding plastics, the interface of the two parts is specially designed to concentrate the melting process. One of the materials usually has a spiked energy director which contacts the second plastic part. The ultrasonic energy melts the point contact between the parts, creating a joint. This process is a good automated alternative to glue, screws or snap-fit designs.

1. *Ultrasonic welding for plastic parts of automotive door trim*

Ultrasonic spot welding is an assembly technique for joining two similar thermoplastic components at localized points with no preformed hole or energy director. Spot welding produces a strong, structural weld and lends itself to large parts, sheets of extruded or cast thermoplastic, corrugated thermoplastic board, and parts with complicated geometry and hard-to reach joining surfaces.

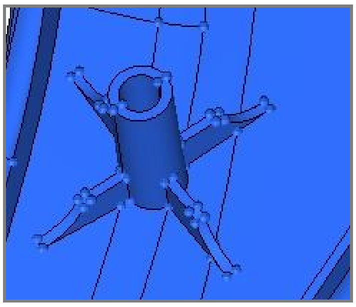


Fig 1 : Welding cylinder

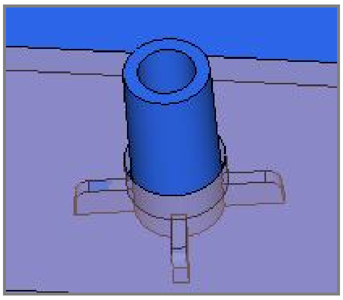


Fig 2 : Welding location

Fig 3 : View of Physical ultrasonic weld

Vibrating ultrasonically, the pilot of the spot welding tip passes through the top component. The molten plastic displaced is shaped by a radial cavity in the tip and forms a neat, raised ring on the surface. Simultaneously, energy is released at the interface producing frictional heat. As penetration of the bottom section is made with the tip, displaced molten plastic flows between the two surfaces into the surrounding interface area and forms a permanent molecular bond. A general rule for spot welding is that the top sheet thickness should be less than or equal to the bottom sheet thickness. The standard tip produces a head having a diameter three times the thickness of the top layer. The length of the protruding tip is one and one-half times the thickness of the top layer.

The ultrasonic weld machine used for this particular application is called as ultrasonic spot welding machine.

Fig 4 : Ultrasonic spot welding machine and its application

It is primarily used for point-by-point riveting, welding and molding of thermoplastic as shown in Fig 4. With the modular integrated circuit, it has strong output power and is easy for operation.

The built-in fully-automatic protection circuit ensures safe application and stable and reliable operation. It has two types of guns, the one is straight and other is piston type gun. The piston type is gun is little handy as compared to straight type gun as below.

Fig 5 : Piston Type Gun

Fig 6 : Stright Type Gun

The benefits of ultrasonic welding are that it is much faster than conventional adhesives or solvents. The drying time is very quick, and the pieces do not need to remain in a jig for long periods of time waiting for the joint to dry or cure. The welding can easily be automated, making clean and precise joints; the site of the weld is very clean and rarely requires any touch-up work.

III. CAE MODELLING OF ULTRASONIC WELDS FOR STATIC AND CRASH SIMULATION

A. *Geometric details of parts, FE modelling and CAE approximation:*

Geometry of Parts to be welded is as shown in Fig 7. The joining interface is created by providing welding cylinder in one part and hole in another part. The FE model is built in Hypermesh software for effective and accurate modelling. The ribbing pattern along with its features and geometric details on the parts are carefully captured during meshing. Full filling the element size criteria offers accurate stiffness representation in all the area.

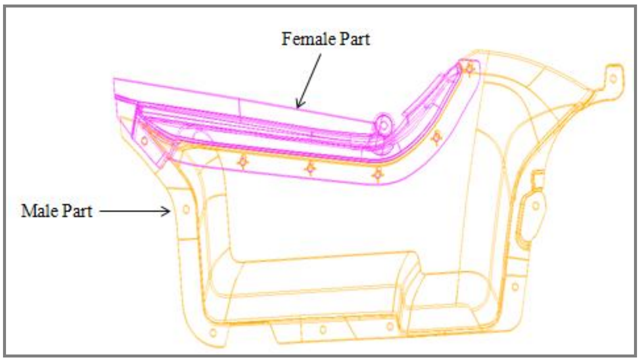


Fig 7: Geometry of Parts to be welded

The yellow part has welding cylinder and pink part has coaxial hole through which welding cylinder passed before welding. The part having welding cylinder is called as male part and part having hole is called as female part as shown in Fig 8.

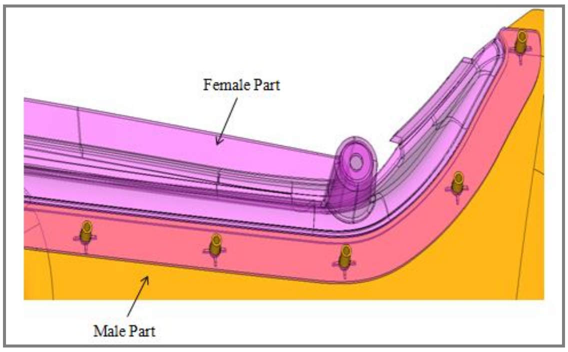


Fig 8: Male and female parts to be welded

In this example the mesh is created at the center of the part thickness. To capture geometric details, element size up to 5mm is considered. The general guideline is used for meshing criteria in order to have good results. The portion of mesh is shown in Fig 9.

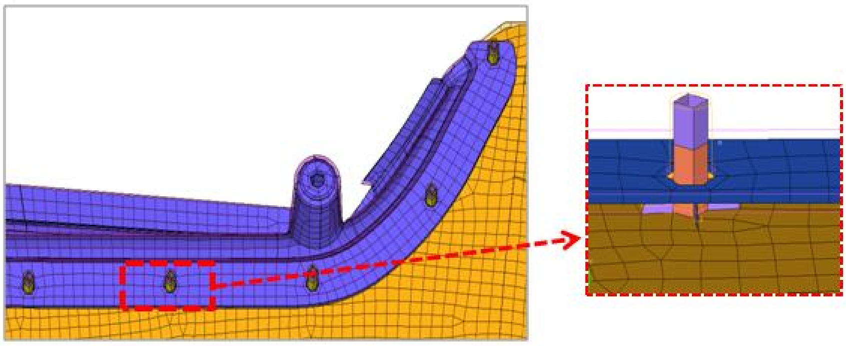


Fig 9: FE model of parts and local view of welding cylinder

While approximating the male-female joining for static and dynamic simulations the cylinder portion above surface of female part is neglected as in Fig 10. For static simulations with Abaqus, the ultrasonic welding is represented by 1D connector element having behavior of physical welding. For crash simulations with LS-Dyna ultrasonic welding is simulated by SPOTWELD and for PAMCRASH welding is simulated by Plink.

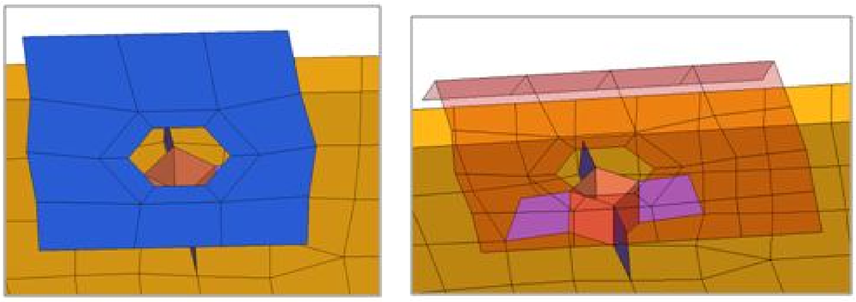


Fig 10: Approximation of welding cylinder

B. Weld Modelling for Static solver Abaqus:

At first, the rigid elements are created on both male and female part. The center nodes of these elements are co-axial to welding cylinder axis.

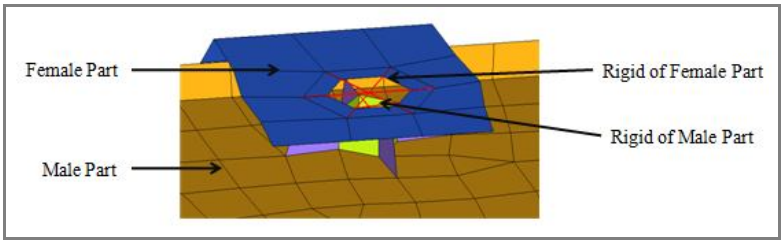


Fig 11: Rigid link assignment

Then the center nodes of these rigid are connected by a connector element as shown in Fig 12. A local axis system is created to control the behavior of connector element.

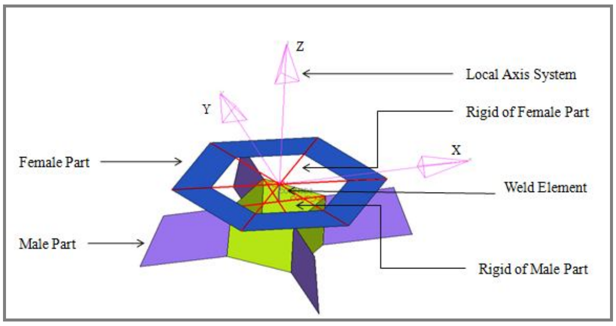


Fig 12: FE modelling of weld joint for Abaqus solver

The various connector configurations available with Abaqus solver are as below

AXIAL	SLIDE-PLANE	EULER	BEAM	TRANSLATOR	FLOW-CONVERTER
CARTESIAN	SLOT	FLEXION-TORSION	CVJOINT	UJOINT	RETRACTOR
JOIN	ALIGN	REVOLUTE	CYLINDRICAL	WELD	SLIPRING
LINK	CARDAN	ROTATION	HINGE	BUSHING	PROJECTION CARTESIAN
RADIAL-THRUST	CONSTANT VELOCITY	UNIVERSAL	PLANAR	ACCELEROMETER	PROJECTION FLEXION-TORSION

After choosing a configuration, a connector property is created for that particular configuration. A connector property describes the connector section and connector behavior. The most commonly used connector section is cylinder section, the below keyword script informs the connector behavior.

```
*CONNECTOR BEHAVIOR, NAME = CONNECTOR
*CONNECTOR ELASTICITY, COMPONENT = 1
     100.0,        0.0,        0.0
*CONNECTOR ELASTICITY, COMPONENT = 3, RIGID
*CONNECTOR ELASTICITY, COMPONENT = 4, RIGID
*CONNECTOR ELASTICITY, COMPONENT = 5, RIGID
*CONNECTOR ELASTICITY, COMPONENT = 6, RIGID
```

Here COMPONENT number indicates the DOF for that particular connector, in above case the stiffness in X local direction is 100 units and its third translation& other rotational degree of freedom are blocked. Thus, the cylinder stiffness for given model is 100 units and as the local Z direction is blocked, that means there will not be any relative displacement in two parts.

The connector stopping distance can be given, for example the 4 mm stopping distance in local X-direction is applied as

```
*CONNECTOR STOP, COMPONENT = 1
          ,        4.0
```

Similarly it is also possible to assign failure limit to connector element. In some cases, it is important to check failure of US welding in impacting zones. The connector failure is assign with below command

```
*CONNECTOR FAILURE, COMPONENT = 1, RELEASE = ALL
           ,          ,          ,       500.0
```

Here RELEASE keyword controls the DOF to be released. In given example, the connector will fail in all DOF once it reaches to stiffness limit of 500 units.

C. *Weld Modelling for CRASH solver LS-Dyna*

1. *Creating Spot weld*

In this method, the holes from male and female parts are filled by creating elements in separate component. In Fig 13, the pink element shows the filled holes.

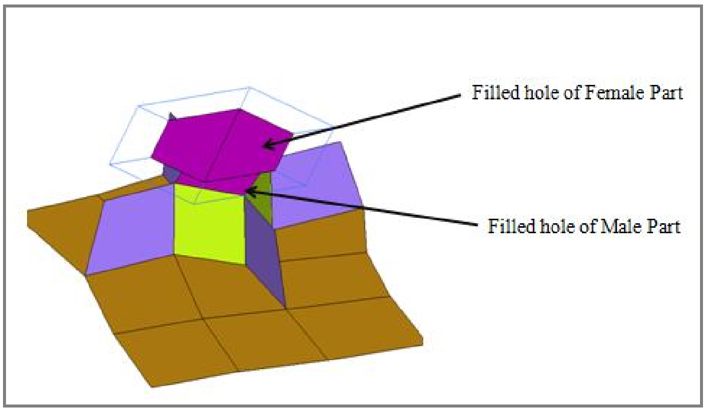


Fig 13: FE modelling to create Spotweld

The spot weld is created by using below keywords *CONSTRAINED _SPOTWELD. The data lines in the command will have below tabular information

Variable	N1	N2	SN	SS	N	M	TF	EP
Type	I	I	F	F	F	F	F	F
Default	none	none	optional	optional	none	none	1.E+20	1.E+20

2. *Creating beam*

Beam creation involves below steps

a. Create element beam.
b. Attribute section beam to part.
c. Attribute material to part.

a. Create element beam :

The center nodes of rigid from both male and female part are connected by BEAM element. The syntax for the keyword is as below

*ELEMENT_BEAM

ID	PID	N1	N2	N3
54196	209	57764	57756	0

ID = element number; PID = Number of component containing beam element
N1 = first node of BEAM; N2 = second node of BEAM

It is important to have N1 on center node of rigid on male part and N2 on center node of rigid on female part as shown in Fig 14.

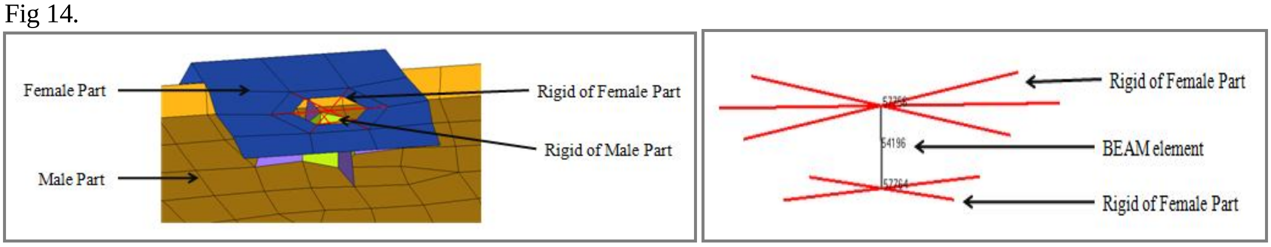


Fig 14: FE modelling of BEAM

b. Attribute section beam to part.

The section beam describes the element formulation, shear factor, Quadrature rule for integrated beam and co-ordinate system id/number

*SECTION_BEAM

id	ELFORM	[SHRF]	[QR]	[CST]	[SCOOR]		
10	6	0.833	2.0	0.0	0.0		
[VOL]	[INER]	CID	[CA/DOF1]	[OFSET/DOF2]	[RRCON]	[SRCON]	[TRCON]
1.000	0.000	0	0.000	0.000			

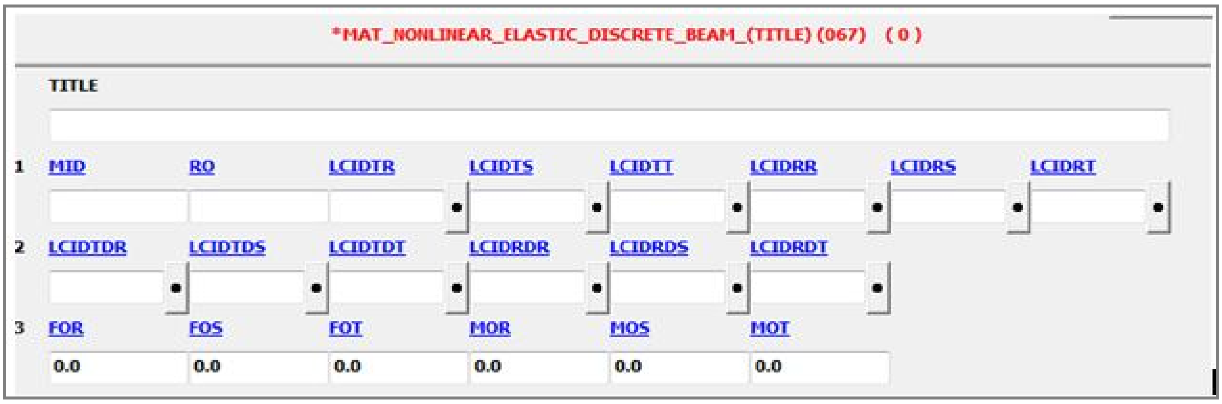
ELFORM = element formulation; SHRF = shear factor, QR = Quadrature rule for beam; CID = Co-ordinate system ID. Following table gives brief information for all the available options of ELFORM, QR, CID and CST.

Here ELFORM 6 indicates Discret beam, QR 2.0 means Gauss Quadrature, CST 0 indicates the dafault coordinate system is rectangular global coordinate system.

c. Attribute material to part :

For material there are two choices viz ***MAT_NONLINEAR _ELASTIC_DISCRETE_BEAM*** *and****MAT_NONLINEAR _PLASTIC_DISCRETE_BEAM***

The elastic beam is defined with below parameter

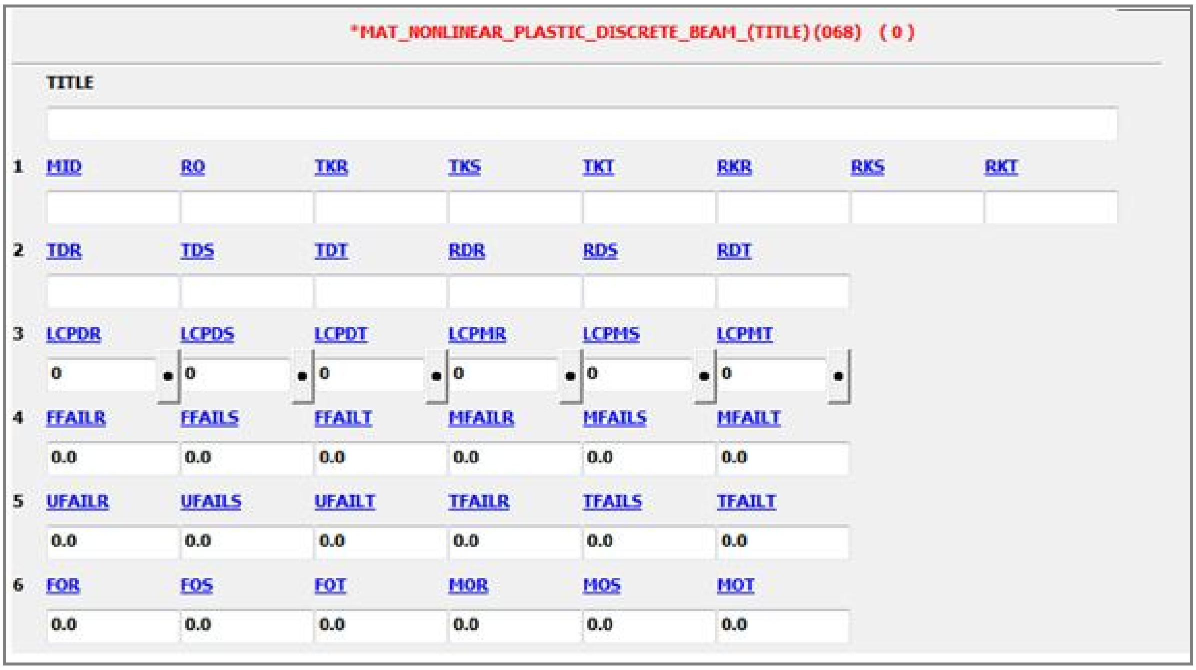


*MAT_NONLINEAR_ELASTIC_DISCRETE_BEAM_(TITLE) (067) (0)

TITLE

1	MID	RO	LCIDTR	LCIDTS	LCIDTT	LCIDRR	LCIDRS	LCIDRT
2	LCIDTDR	LCIDTDS	LCIDTDT	LCIDRDR	LCIDRDS	LCIDRDT		
3	FOR	FOS	FOT	MOR	MOS	MOT		
	0.0	0.0	0.0	0.0	0.0	0.0		

The **plastic beam** is defined with below parameter



*MAT_NONLINEAR_PLASTIC_DISCRETE_BEAM_(TITLE) (068) (0)

TITLE

1	MID	RO	TKR	TKS	TKT	RKR	RKS	RKT
2	TDR	TDS	TDT	RDR	RDS	RDT		
3	LCPDR	LCPDS	LCPDT	LCPMR	LCPMS	LCPMT		
	0	0	0	0	0	0		
4	FFAILR	FFAILS	FFAILT	MFAILR	MFAILS	MFAILT		
	0.0	0.0	0.0	0.0	0.0	0.0		
5	UFAILR	UFAILS	UFAILT	TFAILR	TFAILS	TFAILT		
	0.0	0.0	0.0	0.0	0.0	0.0		
6	FOR	FOS	FOT	MOR	MOS	MOT		
	0.0	0.0	0.0	0.0	0.0	0.0		

D. Modelling for crash solver PAMCRASH

Plink formation is used to represent weld in Pamcrash. The set of cards under the keyword PLINK defines a mesh independent point connection object like a spot weld. Steps of Creating a PLINK are

1. First step is common like spot weld in LS_Dyna i.e. to fill the holes from cylinder top of male part and hole on female part.
2. Then PLINK is created by selecting the filling element. Plink is seen one of closing element.

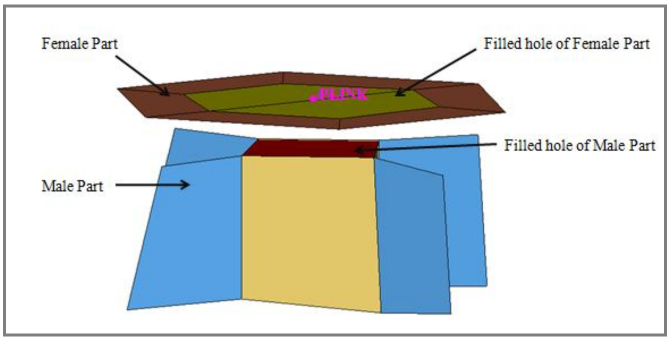


Fig 15: FE modelling of PLINK

3. Then Plink material is created with using below keywords syntax

```
$#          IDMAT    MATYP              RHO    ISINT     ISHG   ISTRAT    IFROZ
MATER /         7      302           1E-009        0        0        0        0
$# BLANK AUXVAR1 AUXVAR2 AUXVAR3 AUXVAR4 AUXVAR5 AUXVAR6      QVM THERMAL    IDMPD
                0       0       0       0       0       0       1.        0        0
$#TITLE
NAME PLINK_PLASTIC
$#  SLFACM      FSNVL     DELTNL      STNOR      STTAN      IFLGC      BLANK    TLSTIF
       0.1         0.         0.       0.0        0.0          0
$#   I3DOF     TOLCOR       IDRUP
         0         0.           1
```

The material type used for Plink is **MAT 302,** the density value (**RHO**) is same of density of male part material. The IDRUP is the rupture model ID and the keyword syntax is as below

```
$*****************************************************************************
$#          NRUPT    IRUPT    IFMON
RUPMO /         1        0        0
$#                                                                        TITLE
NAME PLINK
$# BLANK    FAILT    FAILD   AFAILN   AFAILS       A1       A2     INTF       D1       D2
               0.       0.       0.       0.       1.       1.       20      0.1       1.
$*****************************************************************************
```

IV. FORCES IN THE WELD AND ITS EVALUATION IN CAE

A. Forces in Ultrasonic weld

The ultrasonic weld undergoes axial tension and shear loading. It does not undergo axial compression. After welding, the gap between the male and female part is maintained by un-melted cylinder stem. This cylinder portion normally does not get compress during loading by external force, thus there is no compression force in such kind of welds. Fig 16. shows the CAD cross section at welding location.

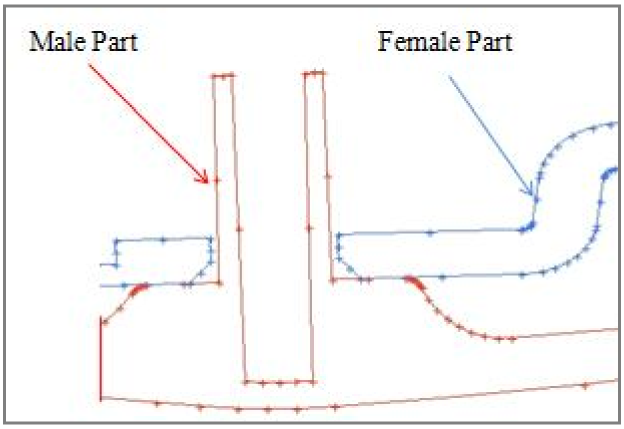


Fig 16: Parts to be welded

During modelling of weld, the local axis system decides the axial and shear direction irrespective of global orientation of weld in vehicle axis system. In given study, the local Z shows the axial direction of load and local X shows shear direction of force as shown in Fig 17. It is possible to assign the failure limits in axial and shear direction.

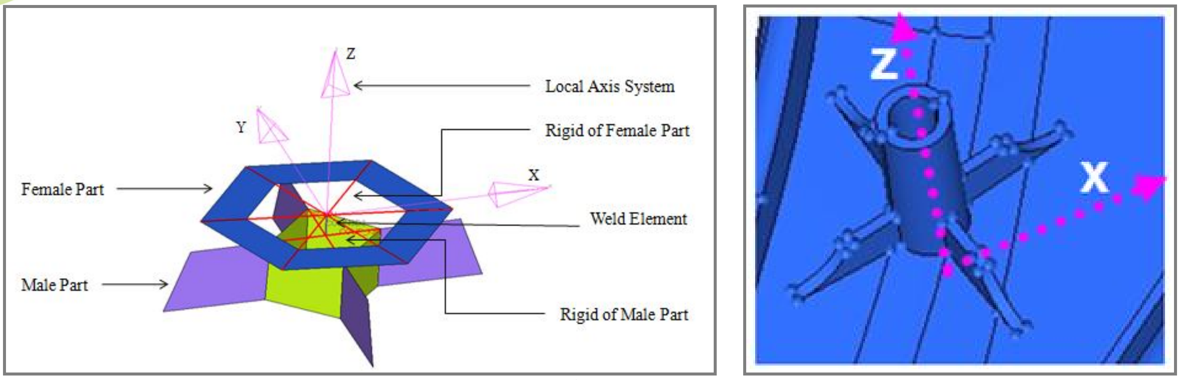


Fig 17: FE modelling of weld joint

B. Post processing in CAE

The reaction forces coming in welding element can be plotted against applied load. The Fig 18 and Fig. 19 shows the Axial and Shear force coming in the welding element for given type of simulation. If the failure limits are known then weld failure can be predicted based the maximum force reached in simulation. The maximum induced axial force in weld of current model is 9.5 N and maximum induced shear force is 4.5N. The failure limit of axial force is 15N and shear force is 7N hence the welds in current assembly are safe.

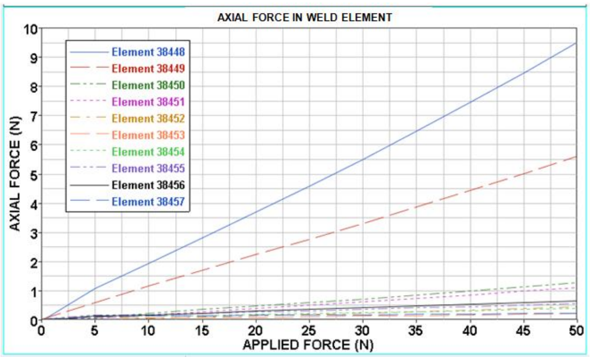


Fig 18: Axial Forces in weld element

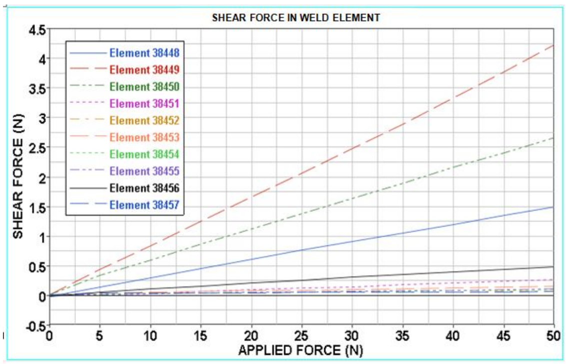


Fig 19: Shear Forces in weld element

The simulation result is usually evaluated through the means of qualitative and quantitative method. In this case, qualitative there should not be unnecessary rise or drop in reaction force and qualitative method means comparison of maximum forces with the failure limit.

V. **CONCLUSION**

The data presented shows that FEM can be used to analyze physical behavior of ultrasonic weld joint used in joining of automotive plastic parts. Some important conclusion of this study were listed below

- The methodology proposed for modelling of weld is highly useful for preparing FE model for static and crash analysis.
- The information given on thickness of parts is important consideration in design of part.

With the discussed post processing method, weld failure can be predicted; redesigning of weld is possible without testing of physical prototype.

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