Parametric Study for Evaluating Damageability of Automotive Radiator by Impacting Stones

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Abstract

The performance of automotive engines depends on the adequate heat rejection by radiator. The durability of radiator under all road conditions is an important consideration during the design and development stage, specifically protection of radiators from impacting road debris and stones. A parametric study was conducted to investigate the damageability of radiators by small stone impacts. In this paper, radiator design parameters are studied for damage protection caused by stone impacts. The strain in the radiator material caused by stone impacts has been used as the measure of damageability. The parameters considered for the study are the fin thickness, fin pitch, tube height, tube thickness, tube nose radius, tube depth, stone size and stone speed. The results show that strain is dependent on fin thickness, tube thickness, stone size and stone velocity. Also strain is insensitive to Tube nose radius, tube construction type, and tube depth.

1.0 Introduction

Automotive radiator is a heat exchanger which helps reject heat from the hot fluid transported from the engine by circulating it through radiator tubes which are surrounded by fins. In our study the radiator fins and tubes are constructed from Post Brazed Aluminum (Figure 1).

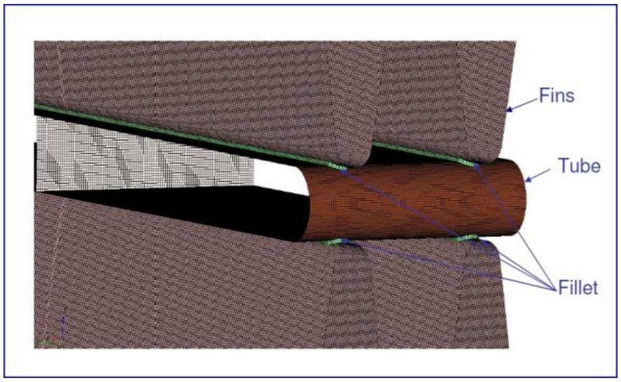


Figure 1 – Tube and Fin Construction

The probability of stone hitting the radiator is function of design of grill openings, the distance between the grill and the radiator, the mounting of the radiator, type of the road and road conditions. The probability of stone impact is very high with large grill openings. Stone impact avoidance is possible in the early design and packaging phase of front end components by optimizing the size and shape of the grill openings.

Radiator function as a heat exchanger is highly dependent on the ambient air flow through the radiator. Design team is often challenged by conflicting design requirements – larger grill opening are desired for effective cooling of the hot fluid but smaller openings are desired for

damage avoidance by stone impacts. If damage is not detected early, it may result in fire or cracking the engine block due to overheat. Even if radiator damage is detected early the replacement cost of radiator is significant which results in increased OEM warranty cost.
Integrity of radiator against stone impact is a design requirement which must be met during the product design stage to withstand stone impacts. Automotive OEMs have developed design specifications, and also component level tests in order to assure robust design of radiators. Figure 2 and 3 show the damage observed due to stone impacts during day to day usage of an automobile.

In this study, an effort is made to evaluate the design parameters of a radiator that may be considered at early development stage for robust design. Moreover, minimum values of these parameters are established as the design guidelines.

Figure 2 – Radiator Damage

2.0 Theoretical Formulation

The material domain of the radiator is considered as a continuum.

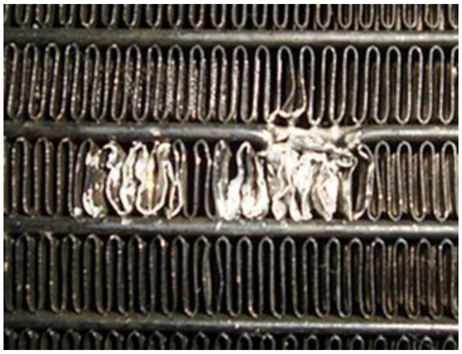


Figure 3-Radiator Damage

Kinematics

The radiator body is a set of particles. A typical particle of radiator is denoted by its position vector **X** at initial time t_0. The domain of **X** at time t_0 is called undeformed configuration of the body. Let **x** denote the position of particle P at time t. The motion of particle P is descried by the vector function [1]:

$$x = \chi(X,t) \tag{2.1}$$

For a fixed X, (2.1) gives the trace of particle P as time t increases. At a fixed time t, (2.1) gives the position of all particles of the radiator body. This motion is assumed to be one-to-one so that (2.1) can be inverted and written as

$$x = \chi^{-1}(X,t) \tag{2.2}$$

The velocity and accelerations of particle P are given by

$$\dot{x}(X_{,i}) = \frac{\partial \chi(X,t)}{\partial t} \tag{2.3}$$

$$\ddot{x}(X_{,i}) = \frac{\partial \chi(X,t)}{\partial t} \qquad (2.4)$$

The governing equations for Langrangian formulation are given below [2]3.

Governing Equations

The momentum equation is,

$$\sigma_{ij,j} + \rho f_i = \rho \ddot{x}_i \qquad (2.5)$$

Satisfying the boundary condition,

$$\sigma_{ij} n_i = t_i(t) \qquad (2.6)$$

On boundary δ b $_{1,}$ the displacement boundary conditions,

$$x_i(X_\alpha, t) = D_i(t) \qquad (2.7)$$

On boundary δ b $_{2,}$ the contact discontinuity,

$$(\sigma_{ij}^{+} - \sigma_{ij}^{-})n_i = 0 \qquad (2.8)$$

Mass conservation is trivially stated,

$$\rho V = \rho_0 \qquad (2.9)$$

Where V is the relative volume and ρ_0 is the reference density.

The energy equation is

$$\dot{E} = Vs_{ij}\dot{\varepsilon}_{ij} - (p+q)\dot{V} \qquad (2.10)$$

LSDYNA3D is used to compute strains developed in the radiator structure due to stone impact. The problem is modeled as high speed impact problem. Explicit formulation is deployed which means that we are solving the following equation:

$$ma^n + cv^n + kd^n = f^n \qquad (2.11)$$

Where n = time step. Where kd^n is the internal force in the structure. The basic problem is to determine the displacement d $^{n+1}$, at time t $^{n+1}$. The above dynamic solution can be re-written as:

$$\text{Explicit: } d^{n+1} = f(d^n, v^n, a^n, d^{n-1}, v^{n-1}, \ldots) \qquad (2.12)$$

All these terms are known at time state "n" and thus can be solved directly.

Constitutive Model – Piecewise Elastoplasticity

At low stress levels in elastoplastic materials the stresses, σ_{ij}, depends only on the state of strain, however, above a certain stress level, called the yield stress, $\sigma_y(a_i)$, nonrecoverable plastic deformations are obtained. The yield stress changes with increasing plastic deformations, which are measured by internal variables, a_i.

In the uniaxial tension test, a curve like in Figure 4 is generated where logarithmic uniaxial strain is plotted against the uniaxial true stress which is defined as the applied load P divided by the cross-sectional area, A.

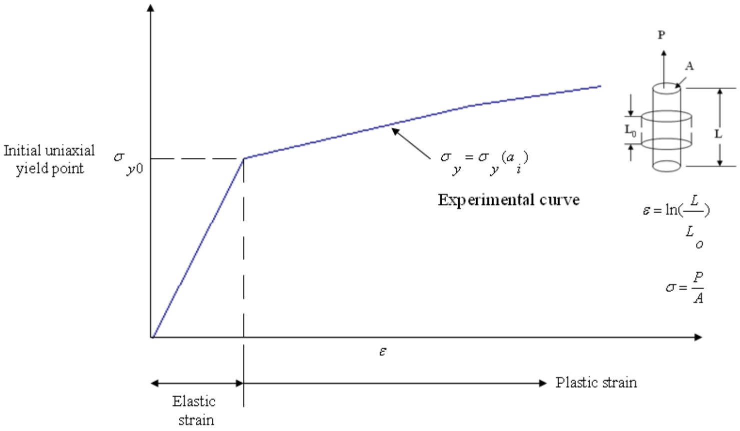


Figure 4 - Plastic Behavior

This model includes strain rate effects. The yield function Φ is a function of Deviatoric stresses, and is given by:

$$\phi = \frac{1}{2} s_{ij} s_{ij} - \frac{\sigma_y^{\ 2}}{3} \leq 0 \qquad (2.13)$$

Where

$$\sigma_Y = \beta\left[\sigma_0 + f_h(\varepsilon^p{}_{eff})\right] \qquad (2.14)$$

Here, linear hardening of the form $f_h(\varepsilon^p{}_{eff}) = E_p\ (\varepsilon^p{}_{eff})$ is assumed where E_p (plastic hardening modulus) and $\varepsilon^p{}_{eff}$ (effective plastic strain) are given in Equations

$$E_p = \frac{E_t E}{E - E_t} \qquad (2.15)$$

$$\varepsilon^P_{eff} = \int (\frac{2}{3} \dot{\varepsilon}^p_{ij} \dot{\varepsilon}^p_{ij})^{1/2} dt \qquad (2.16)$$

Parameter β accounts for strain rate effects. In the implementation of this material model, the deviatoric stresses are updated elastically the yield function is checked, and if it is satisfied the deviatoric stresses are accepted. If it is not, an increment in plastic strain is computed.

$$\Delta\varepsilon_{eff}^{p} = \frac{(\frac{3}{2}S_{ij}^{*}S_{ij}^{*})^{1/2} - \sigma_{y}}{3G + E_{p}} \tag{2.17}$$

Where G is the shear modulus and E_p is the current plastic hardening modulus. The trial deviatoric stress state S_{ij}^{*} is scaled back

$$S_{ij}^{n+1} = \frac{\sigma_{y}}{(\frac{3}{2}S_{ij}^{*}S_{ij}^{*})^{1/2}} S_{ij}^{*} \tag{2.18}$$

Radiator is modeled with shell elements, for these elements the above equations apply, but with the addition of an iterative loop to solve for the normal strain increment, such that the stress component normal to the mid surface of the shell element approaches to zero.

3.0 Parametric Study

Radiator is designed to condition the engine fluid to a required temperature. This function is delivered by right sizing the radiator which includes the number and size of tubes and fins, and strategy of fluid flow through the radiator. The structural integrity of radiator against the damageability due to stone impact only depends on many parameters of tube and fin design. Fins are designed to provide spacing and structural strength to tubes. In the following paragraph these parameters are discussed:

1. Construction of the tube:

   (a) Folded B (Figure 5) – When the tube is constructed, both ends are folded in the center and it looks like the letter B.

   (b) Welded (Figure 6) – When the tube is constructed, both the ends are welded together.

2. The Table 1 shows the parameters considered for tube and fin designs parametric scheme.

3. The baseline parameter values are as follows:
   (a) Fin thickness – 0.08 mm,
   (b) Fin Pitch – 3.0/2 mm,
   (c) Tube height – 1.75 mm,
   (d) Tube thickness – 0.2mm,

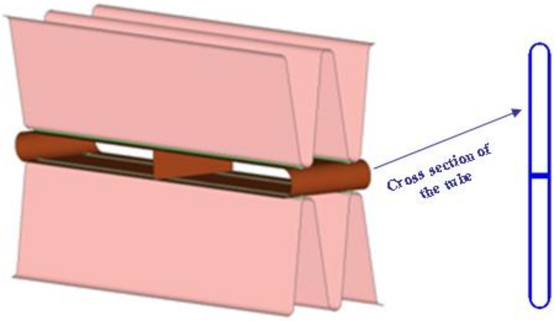


Figure 5 – Folded B Construction

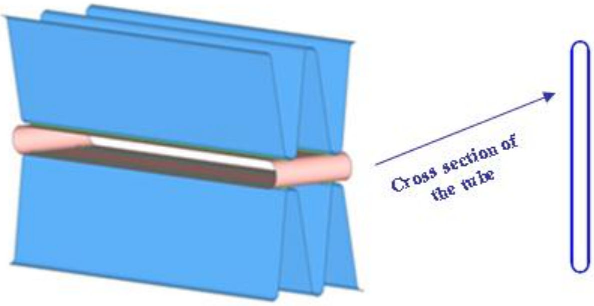


Figure 6 – Welded Construction

(e) Tube nose radius – 0.875 mm,
(f) Tube depth – 25 mm,
(g) Stone size – 2 mm and
(h) Stone speed 30 mph.

4. Externally applied parameters are speed of the stone and size of the stone.

Fin Thickness (mm)	0.04	0.06	0.08*	0.1
Fin Pitch (mm)	2.0/2	2.5/2	3.0/2*	3.5/2
Tube Height (mm)	1.25	1.5	1.75*	2.0
Tube Thickness (mm)	0.1	0.2*	0.3	0.4
Tube Nose Radius (mm)	0.2	0.4	0.6	0.875*
Tube Depth (mm)	15	20	25*	30
Stone Size (mm)	1	2*	4	6
Stone Speed (mph)	15	30*	45	60

*** shows base values**

Table 1 – Showing parameters studied

Figure 7 pictorially shows the definitions of design parameters of tube and fin. The changes in plastic strain versus three discrete values of each parameter are studied.

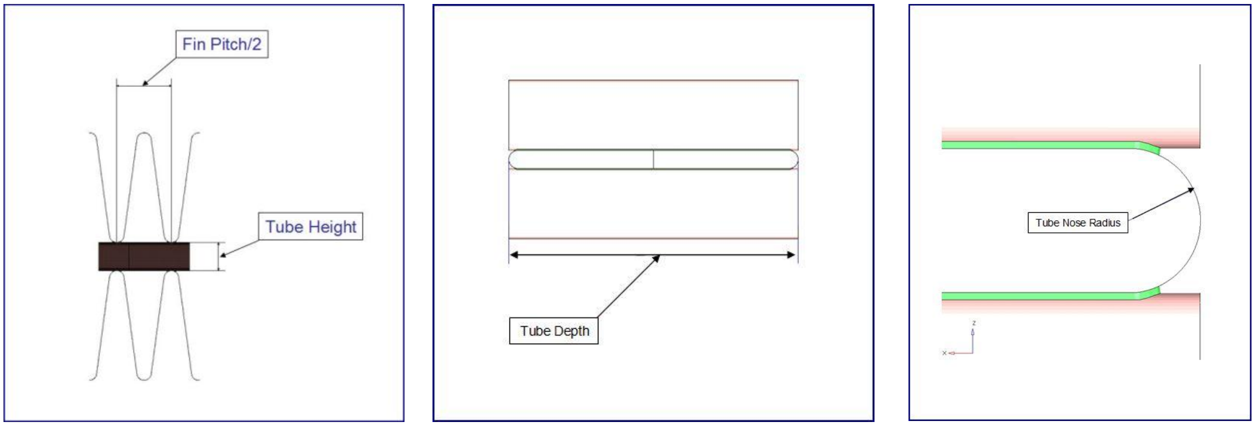


Figure 7 – Various parameters of Radiator
(See Table 1 for parameter dimensions)

Material properties of Post Brazed Aluminum are:

Density = 2.73 g/cc
Modulus of Elasticity = 57186 MPa
Poisson's ratio = 0.33

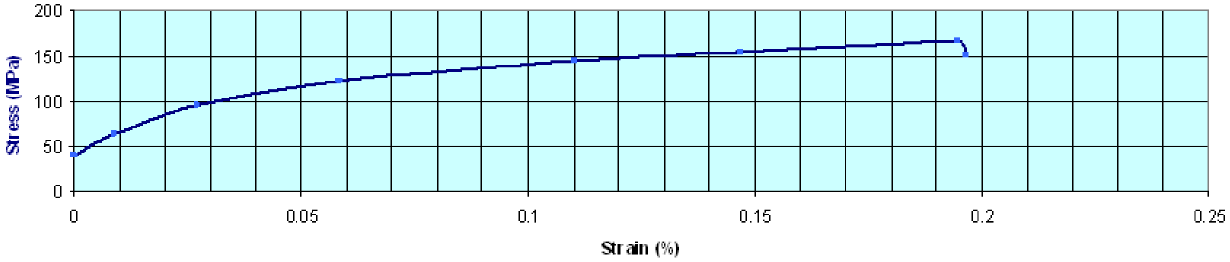


Figure 8 – Stress versus Strain for Aluminum material

4.0 Computation Results

The baseline values for this study are given in 3.0(3). LSDYNA3D has been deployed to obtain computational results. These results are discussed in this section.

Plastic Strain Insensitive to the change in the parameters values

For the baseline design, speed and stone size, the construction types, folded B or welded, do not affect the plastic strain in tube (Figures 10 to 16). Similarly, the fin thickness, fin pitch, and tube depth do not affect the plastic strain in the tube. See Figures 9, 10 and 14, respectively.

Plastic Strain Slightly Sensitive to the change in the parameters values

For the baseline design, speed and stone size, the changes in tube height, tube nose radius and tube depth showed insignificant changes in the plastic strain of the tube.
See Figures 11 and 13, respectively

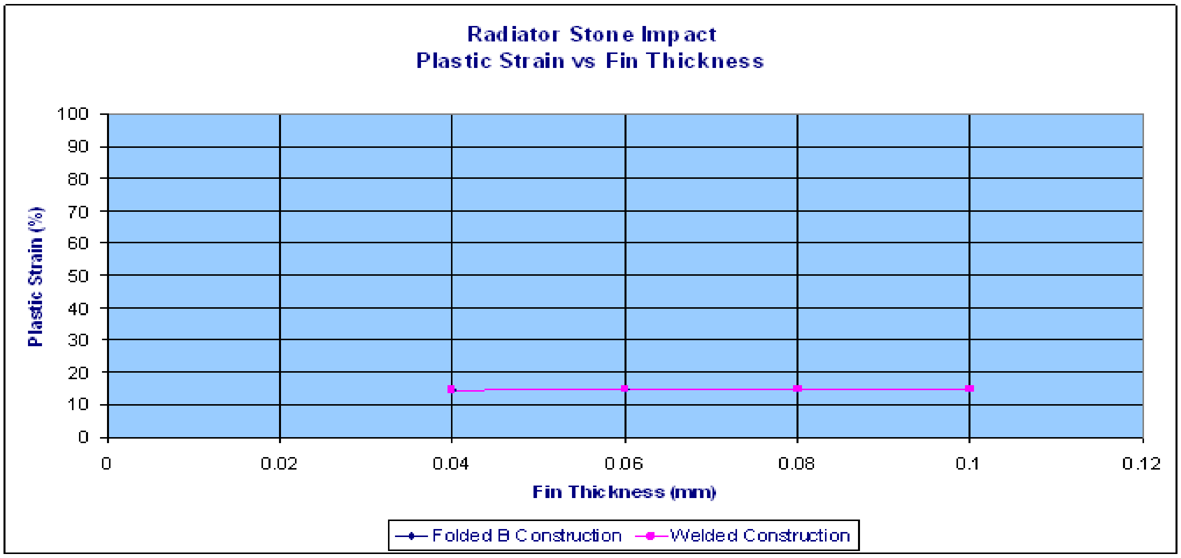
Plastic Strain Insensitive to the change in the parameters values

For the baseline design, speed and stone size:

a) For tube thicknesses from .1 to .4 mm the plastic strain dropped from 23% to 6% which is significant to achieve robust design against stone impact (Figure 12).

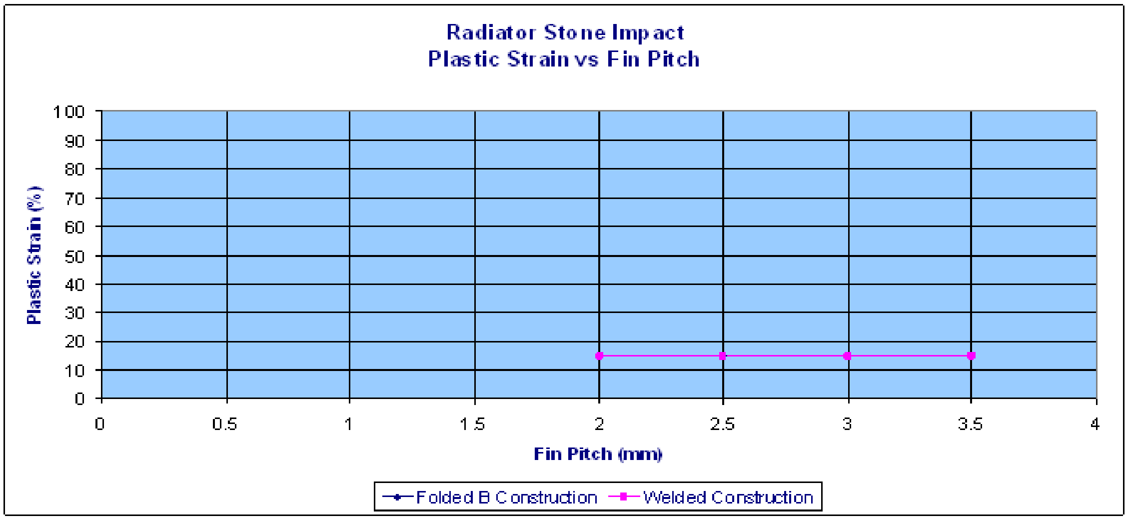
b) For stone sizes 1 to 6 mm, the change in plastic strain was 87% which is substantially significant. It demonstrates that frontend grill mesh size should be small enough to screen stone sizes of greater than 3mm to keep the plastic strain below the yield value of 15% (Figure 15).

c) For stone speeds from 15 to 60 mph, the plastic strain increased from 8% to 35% which is significant. The speed of the impacting stone is noise factor and can not be controlled. The design of tube and the stone shield (grill) has to be robust to meet the requirements. (Figures 16)



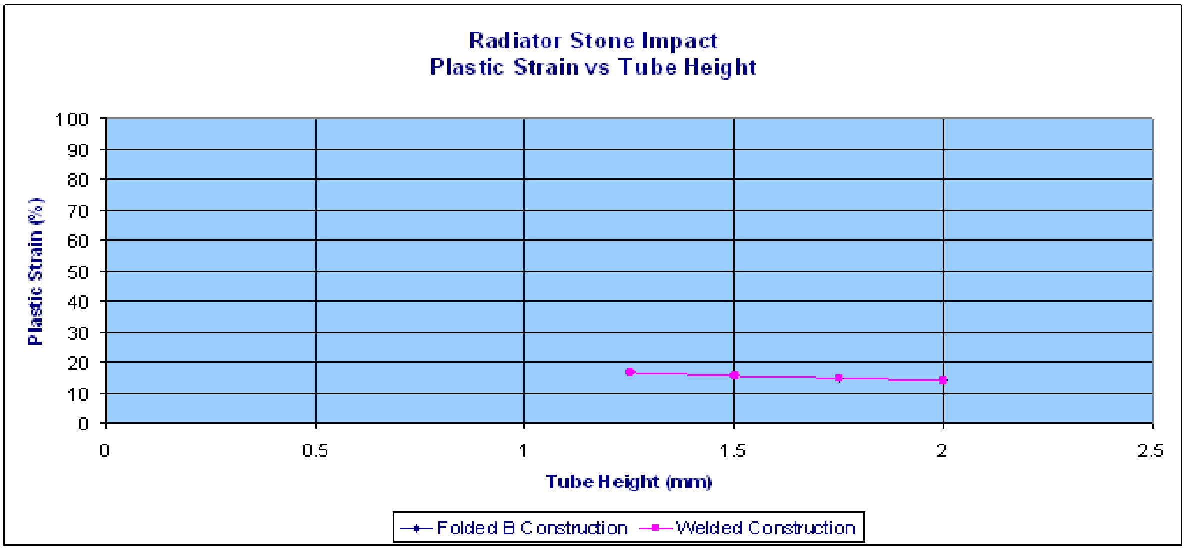
Parameter	Folded B Construction Plastic Strain (%)	Welded Construction Plastic Strain (%)
Fin Thickness 0.04mm	14.62	14.62
Fin Thickness 0.06mm	14.75	14.75
Fin Thickness 0.08mm	14.83	14.83
Fin Thickness 0.1mm	14.87	14.87

Figure 9 – Plastic Strain vs. Fin Thickness



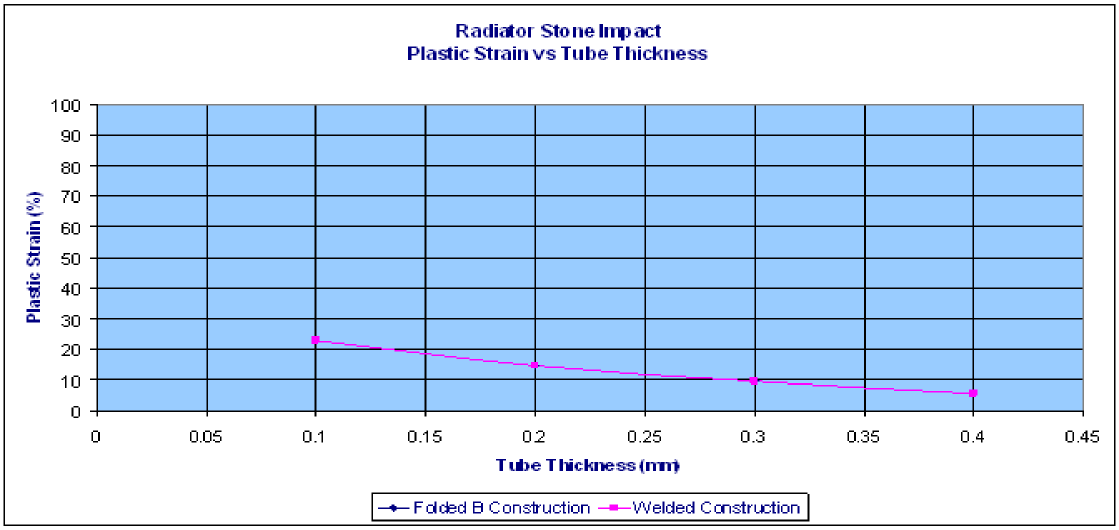
Parameter	Folded B Construction Plastic Strain (%)	Welded Construction Plastic Strain (%)
Fin Pitch 2mm	14.84	14.85
Fin Pitch 2.5mm	14.82	14.82
Fin Pitch 3mm	14.83	14.83
Fin Pitch 3.5mm	14.83	14.83

Figure 10 – Plastic Strain vs Fin Pitch



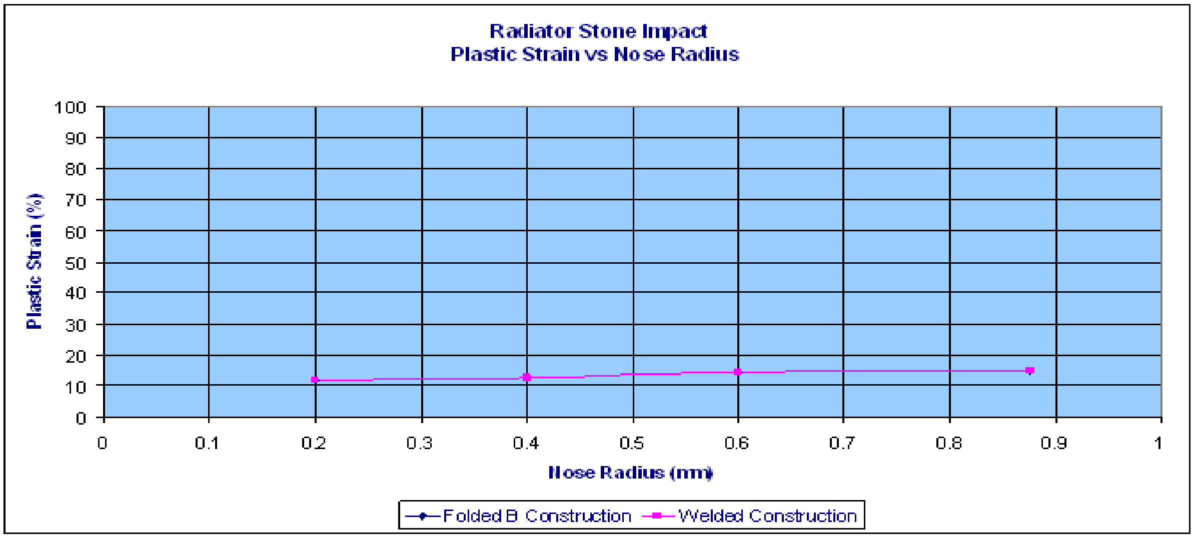
Parameter	Folded B Construction Plastic Strain (%)	Welded Construction Plastic Strain (%)
Tube Height 1.25mm	16.69	16.69
Tube Height 1.5mm	15.37	15.37
Tube Height 1.75mm	14.83	14.83
Tube Height 2.0mm	13.88	13.88

Figure 11 – Plastic Strain vs. Tube Height



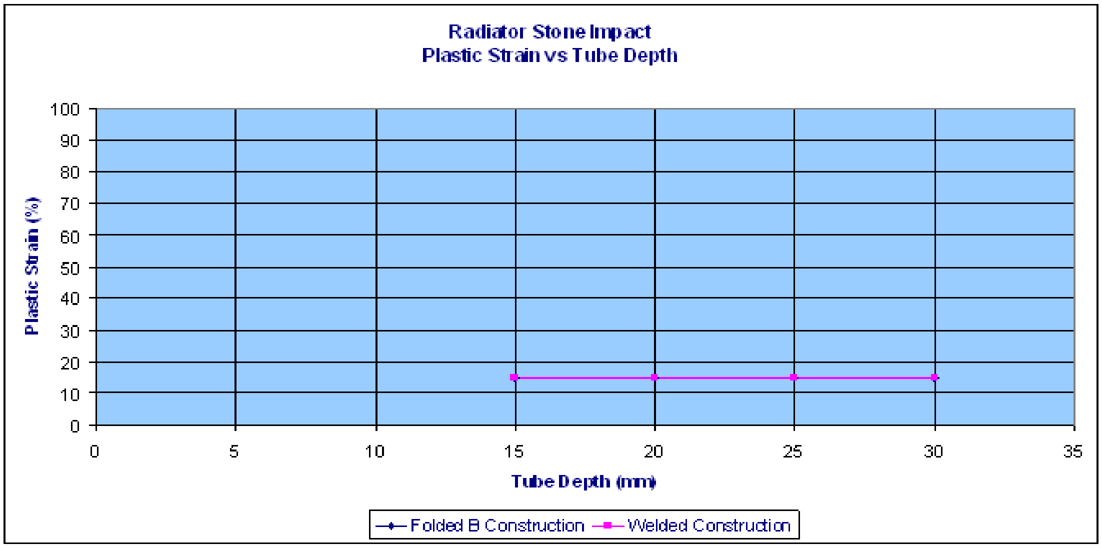
Parameter	Folded B Construction Plastic Strain (%)	Welded Construction Plastic Strain (%)
Tube thickness 0.1mm	23.03	23.04
Tube thickness 0.2mm	14.83	14.83
Tube thickness 0.3mm	9.75	9.7
Tube thickness 0.4mm	5.9	5.9

Figure 12 – Plastic Strain vs. Tube Thickness



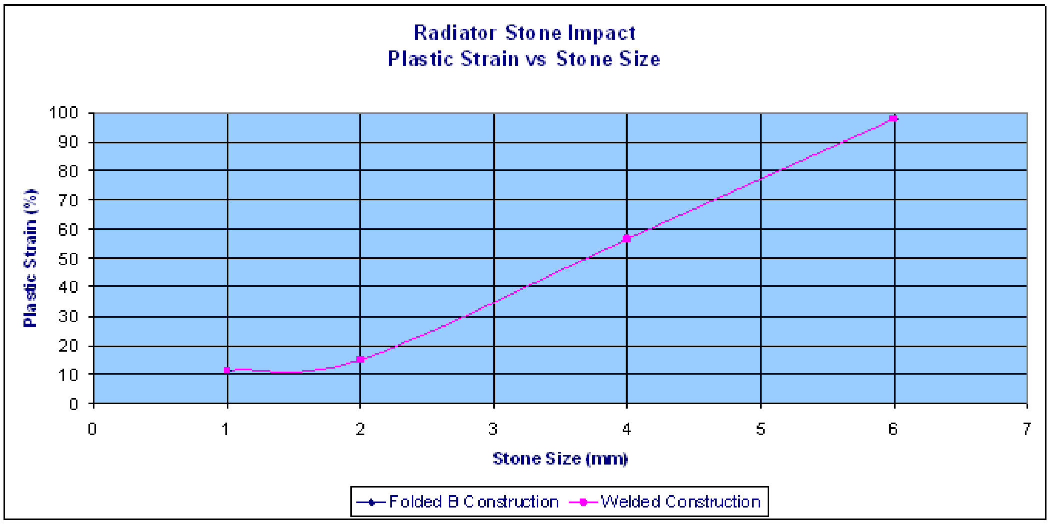
Parameter	Folded B Construction Plastic Strain (%)	Welded Construction Plastic Strain (%)
Tube Nose Radius 0.2mm	11.76	11.76
Tube Nose Radius 0.4mm	12.55	12.55
Tube Nose Radius 0.6mm	14.41	14.41
Tube Nose Radius 0.875mm	14.83	14.83

Figure 13 – Plastic Strain vs. Tube Nose Radius



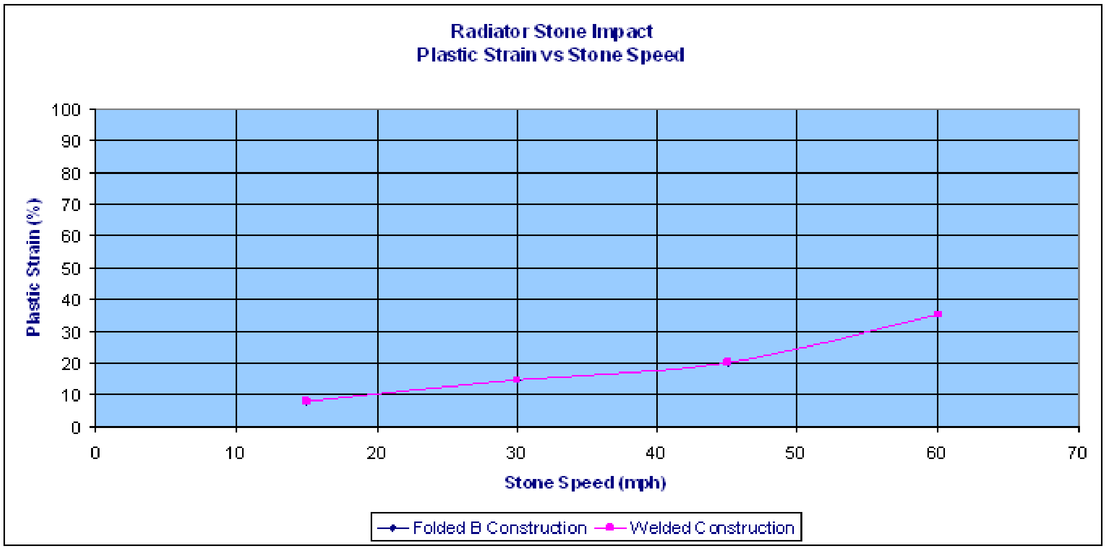
Parameter	Folded B Construction Plastic Strain (%)	Welded Construction Plastic Strain (%)
Depth_15mm	14.75	14.75
Depth_20mm	14.81	14.81
Depth_25mm	14.83	14.83
Depth_30mm	14.83	14.83

Figure 14 – Plastic Strain vs. Tube Depth



Parameter	Folded B Construction Plastic Strain (%)	Welded Construction Plastic Strain (%)
Stone size 1mm	11.07	11.07
Stone size 2mm	14.83	14.83
Stone size 4mm	56.51	56.5
Stone size 6mm	97.66	97.9

Figure 15 – Plastic Strain vs. Stone Size



Parameter	Folded B Construction Plastic Strain (%)	Welded Construction Plastic Strain (%)
Stone speed 15mph	7.95	7.95
Stone speed 30mph	14.83	14.83
Stone speed 45mph	20.04	20.04
Stone speed 60mph	35.39	35.39

Figure 16 – Plastic Strain vs. Stone Speed

5.0 Concluding Remarks

This parametric study suggests that the tube thickness is the key parameter for robust design of the radiator to protect the tube damage due to stone impact. The external noise factor, stone size, should be addressed by the design of the frontend grill mesh opening size.

Future research may be conducted for effect of multi-variable interaction on damageability of radiator by stone impacts.

6.0 References

1. *"The effect of moisture and temperature on the vibrational characteristics of composite structures", presented at the 4th Technical Conference on Composite Materials, American Society for Composites, held at Virginia Polytechnic Institute and State University, Blacksburg, VA, October 3-6, 1989, (with M. V. Gandhi and L. Chao).*
2. *LS-DYNA Theoretical Manual published in May 1998.*

7.0 Acknowledgement

The authors are thankful to contributions made by Calvin Young, Dr. Yi Zhang and Jon Raver of Ford Motor Company for their technical contributions in conducting this parametric study.