Free Vibration Characteristics of Clinched Joints

Xiaocong He, Wenbin Zhang, Biao Dong, Xunzhi Zhu and Shanfeng Gao

Abstract—**Due to the increasing demand for energy-efficient vehicles, there is an increasing need to design lightweight structures and these invariably use lightweight materials which are difficult or impossible to weld. Clinching technology offers an alternative to spot welding especially for joining sheet materials. The present paper deals with transverse free vibration analysis of single lap jointed encastre clinched joints using three dimensional finite element methods (FEM). The focus of the analysis is to reveal the influence on the natural frequencies, natural frequency ratios and mode shapes of these joints caused by variations in the material properties of the sheet materials. Numerical examples show that the transverse natural frequencies of single lap jointed encastre clinched joints increase significantly as the Young's modulus of the sheets increase, but only slight changes are encountered for variations of Poisson's ratio. The mode shapes show that there are different deformations in the jointed section of clinched joints compared with the reference cantilevered beams without joint. These different deformations may cause different natural frequency values and different stress distributions. As expected, odd modes shapes were found to be symmetrical about the mid-length position and even modes were anti-symmetrical. It is also found that the material densities of the sheets have significant effects on the transverse free vibration characteristics of single lap jointed encastre clinched joints**

Keywords—**Clinching, transverse free vibration, sheet material characteristics, finite element method.**

I. Introduction

Due to the need to design lightweight structures such as vehicle body shells, some mechanical joining techniques have been developed for joining advanced materials that are dissimilar, coated and hard to weld [1]. Clinching has also been developed rapidly into a new branch of mechanical joining techniques. The clinching process is a method of joining sheet metal or extrusions by localized cold-forming of materials. The result is an interlocking friction joint between two or more layers of material formed by a punch into a special die. Depending on the tooling sets used, clinched joints can be made with or without the need for cutting. By using a round tool type, materials are only deformed. If a square tool is used, however, both deformation and cutting of materials are required. The principle of clinching with a round tool is given in Fig. 1. Clinching uses less energy and has drawn more attention in recent years.

In the design of mechanical structures which contain clinched joints, the knowledge of the mechanical characteristics of these joints is essential. Consequently, the static and fatigue behavior of these joints has been the subject of a considerable amount of experimental and numerical studies. Gao and Budde [2] have conducted a study on the joining mechanism of clinching. Some basic terms, such as the mechanical contact chains and their symbols and the joint networks, were introduced to establish a basic theory for analyzing the joining mechanism. Hamel et al. [3] developed an elastic-plastic incremental finite element computer code for studying clinch forming with respect to process parameters. The results are compared with experimental data and numerical results calculated with a static implicit method. A comparison studies between round and square clinching tools for high-strength sheet metals have been conducted by Varis [4]. In another work, Varis pointed out several problems encountered in the long-term use of a clinching process and both the lack of systematic maintenance and continuous follow-up are discussed [5]. Pedreschi and Sinha [6] conducted an experimental study of cold formed steel trusses using mechanical clinching and found that the number of clinches has a marked influence on the strength, deformation and failure mode of the trusses. Along with SEM, Carboni *et al.* [7] investigated the fatigue behaviors of clinched joints and found that the influence of joint configuration is not significant. The stress ratio that in fatigue tests, however, will completely changes the failure mode. De Paula *et al.* [8] carried out finite element simulations of the clinch joining of metallic sheets. The simulations covered the effect of these changes on the joint undercut and neck thickness. The relevant geometrical aspects of the punch/die set were determined and the importance of an adequate undercut on the joint strength was confirmed. A parametrical study based on the Taguchi's method, has been conducted by Oudjene and Ben-Ayed [9] to properly study the effects of tools geometry on the clinch joint resistance as well as on its shape. In a recent study [10], a response surface methodology (RSM), based on Moving Least-Square (MLS) approximation and adaptive moving region of interest, is presented for shape optimization of clinching tools. The geometries of both the punch and the die are optimized to improve the joints resistance to tensile loading. However, despite these impressive developments, research in the dynamic properties of clinched joints is relatively unexplored. Hence there is a need for a contribution of knowledge to the understanding of the

Manuscript received March 31 , 2009. This work was supported in part by the Program for Innovative Technology Research Groups in Kunming University of Science and Technology, China.

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vibration characteristics of the clinched joints.

The present paper deals with transverse free vibration analysis of single lap jointed encastre clinched joints using three dimensional finite element methods (FEM). The finite element analyses are carried out using the commercially-available ANSYS FEA program. Numerical examples are provided to show the influence on the natural frequencies, natural frequency ratios and mode shapes of the single lap jointed encastre clinched joints of different characteristics of sheets to be jointed. Transverse free vibration analysis data were used in conjunction with mathematical mode to establish the relationship between the natural frequencies and the Young's modulus. The mode shapes were discussed for investigating the relative amplitudes of the transverse free vibration of the single lap-jointed encastre clinched joints.

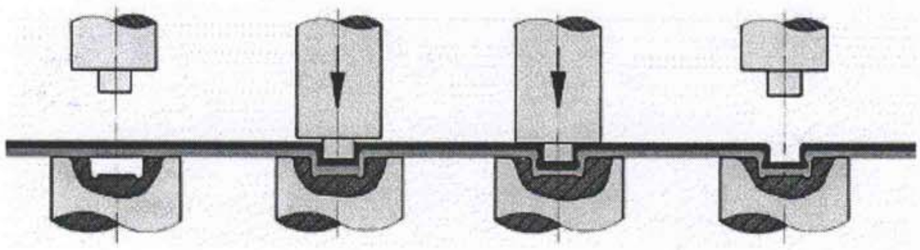

Fig. 1. The principle of clinching with a round tool (TOX® GmbH)

II. Configuration and Properties of Single Lap-jointed Encastre Clinched Joints

The single lap-jointed encastre clinched joints studied in the present work is shown in Fig. 2. The joint includes the upper sheet and lower sheet. The two sheets were of dimensions 0.11 m long ×0.02 m wide ×0.002 m thickness and were joined together in the central part. Table 1 shows the mechanical properties of the sheets. The range of sheet properties considered covers the mechanical properties of various types of lightweight materials such as lightweight alloy and polymers.

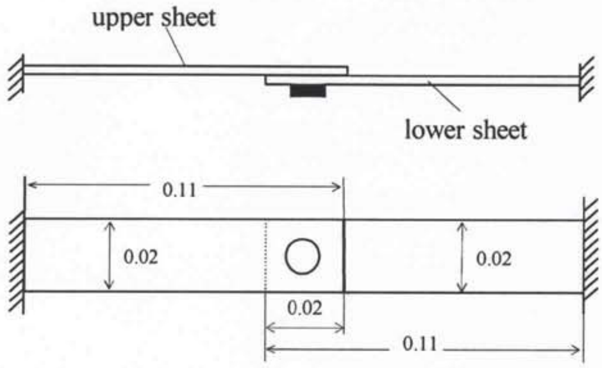

Fig. 2. A single lap-jointed encastre clinched joints

Table 1. Mechanical properties of sheets to be jointed

Sheets	E_s [GPa]	0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100
	v_s	0.3, 0.32, 0.34, 0.36, 0.38, 0.4

III. Finite Element Modelling

The original element mesh of the single lap-jointed encastre clinched joint is shown in Fig. 3. Because of the complex geometry and the three dimensional nature of the free vibration on the single lap-jointed encastre clinched joint, solid187 elements were used to model the joint. Solid187 element is a higher order 3-D, 10-node element which has a quadratic displacement behavior and is well suited to modeling irregular meshes. In order to save computation time small finite elements are used within and around the jointed section and larger elements are used in the outer regions. To obtain the sophisticated features such as design optimization and adaptive meshing, ANSYS Parametric Design Language (APDL) was used in finite element modeling of the single lap-jointed encastre clinched joint. The material parameters of the sheets were input via the APDL input files. The natural frequencies (Eigenvalues) and mode shapes (eigenvectors) of the free vibration of single lap-jointed encastre clinched joints were extracted for different combinations of the Young's modulus and Poisson's ratio of the sheets to be jointed.

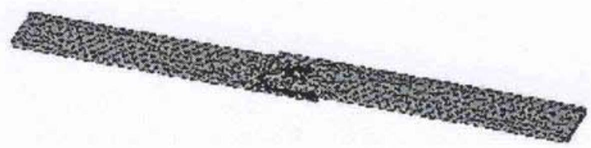

Fig. 3. Original element mesh of the single lap-jointed encastre clinched joint

IV. Free Transverse Vibration Analysis

Each of the values of Young's modulus (given Table 1, E_s) was used with each of the values of Poisson's ratios in an FE analysis. The transverse natural frequencies of the single lap-jointed encastre clinched joints were derived from each computation corresponding to a pair of sheet properties. These results are presented in graphical formats and are discussed in the following.

A. *Effect of Young's modulus of sheets.*

Fig. 4 shows the transverse natural frequencies versus Young's modulus of sheets with ν_s=0.30 and ν_s= 0.40. The material density is 2500 kg/m^3, which is close to the material density of aluminum alloy. In the cases of Poisson's ratios of 0.32, 0.34, 0.36 and 0.38, similar variations of transverse natural frequency with Young's modulus of sheet as in the case of Poisson's ratios of 0.30 and 0.40 are observed. It is clear that the transverse natural frequencies increase greatly as the Young's modulus of sheets increase.

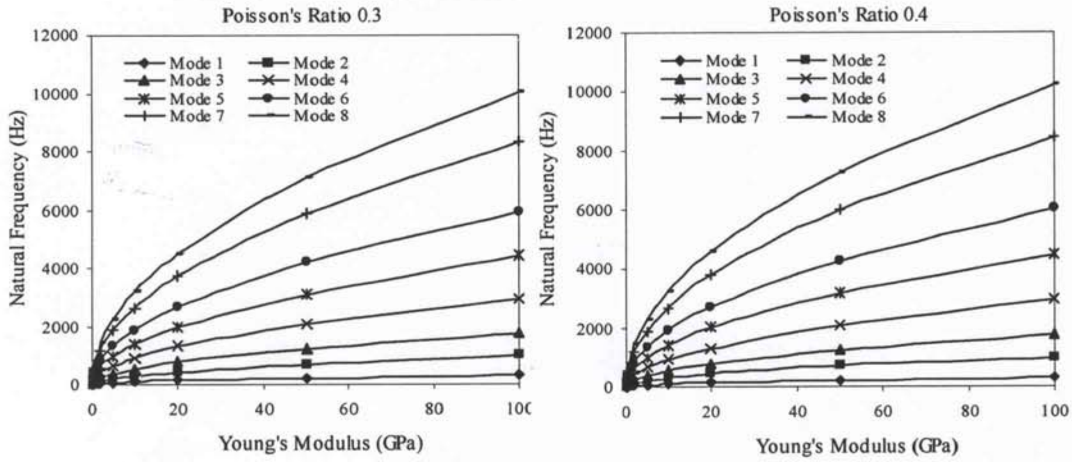

Fig. 4. Transverse natural frequencies versus Young's modulus of sheets

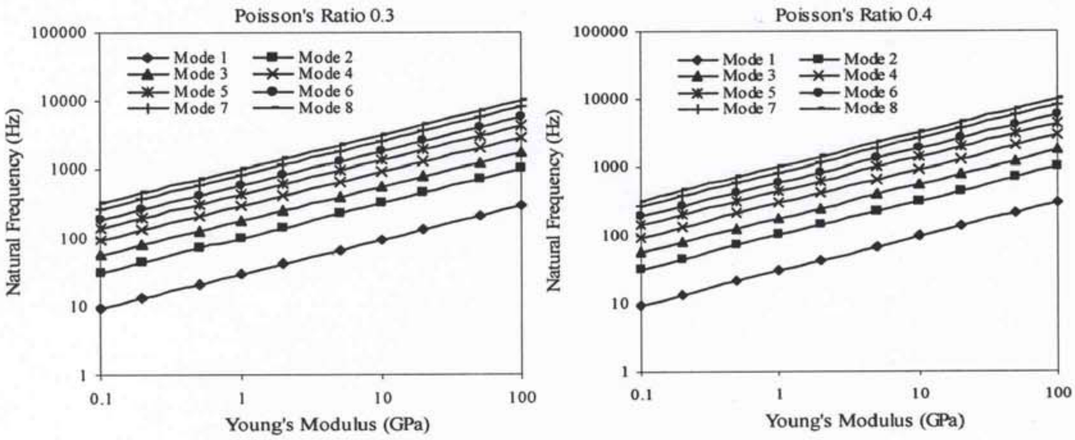

Fig. 5. Relationship between F and E_s in the ln-ln coordinates

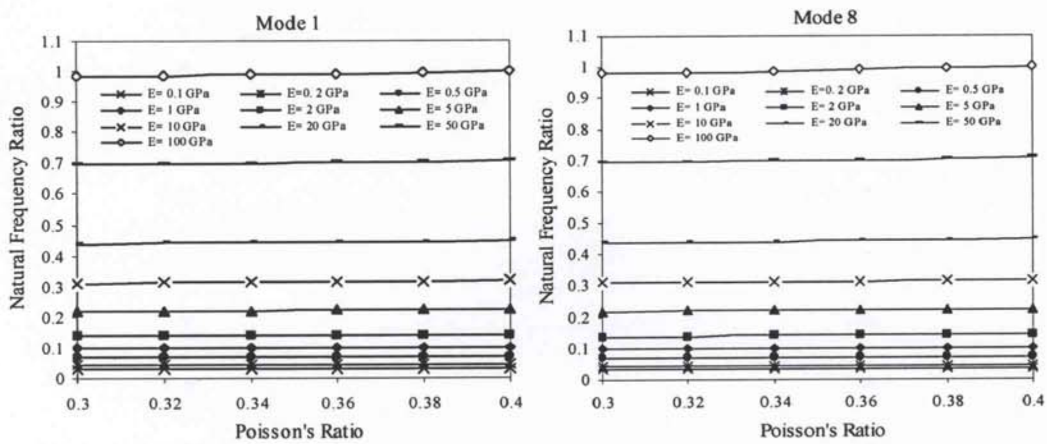

Fig. 6. Transverse natural frequency ratios versus Poisson's ratio of sheets

ISBN:978-988-18210-1-0

In order to find the relationship between the transverse natural frequencies F and the Young's modulus E_s, the natural frequencies were used in conjunction with different type of trendlines. It is fund that the power trendline provides the perfect fit (R-squared value R^2=1) for the relationship between the transverse natural frequencies F and the Young's modulus E_s and a mathematical model of the following type is expected.

$$F = aE_s^{\ 0.5} \tag{1}$$

And it can be rewritten as

$$\ln F = 0.5 \ln E_s + \ln a \tag{2}$$

It is obvious that Eq. (2) is a linear equation in ln-ln coordinates. In other words the transverse natural frequency curves should became a set of parallel straight lines in the ln-ln coordinates. These straight lines have the same slope 0.5 but different intersections with the $\ln F$ axis. Fig.5 shows the straight lines for the case of Poisson's ratios 0.30 and 0.40 in the ln-ln coordinates. For the cases of Poisson's ratios 0.32, 0.34, 0.36 and 0.38, there are similar trends in the variations of the transverse natural frequencies with Young's modulus.

B. Effects of Poisson's ratios of sheets.

Ranges to the first and eighth natural frequency ratios, caused by varying the Poisson's ratio of sheet materials are shown in Fig. 6. In the cases of mode 2 to mode 7, similar variations of natural frequency ratios with Poisson's ratio of sheets as in the case of mode 1 and mode 8 are observed. Here the natural frequency ratio is the ratio of the natural frequency of a mode calculated at a particular Poisson's ratio to the natural frequency of the same mode calculated for a reference encastre beam of the same geometry and dimensions as the single lap-jointed encastre clinched joint but without joint. These values were used in the analysis in order to obtain a reference bound for the transverse natural frequencies of a single lap-jointed lightweight material encastre beam [11]. From Fig. 6 it is seen that the natural frequency ratios of the transverse modes increase slightly as the Poisson's ratio of sheets increase.

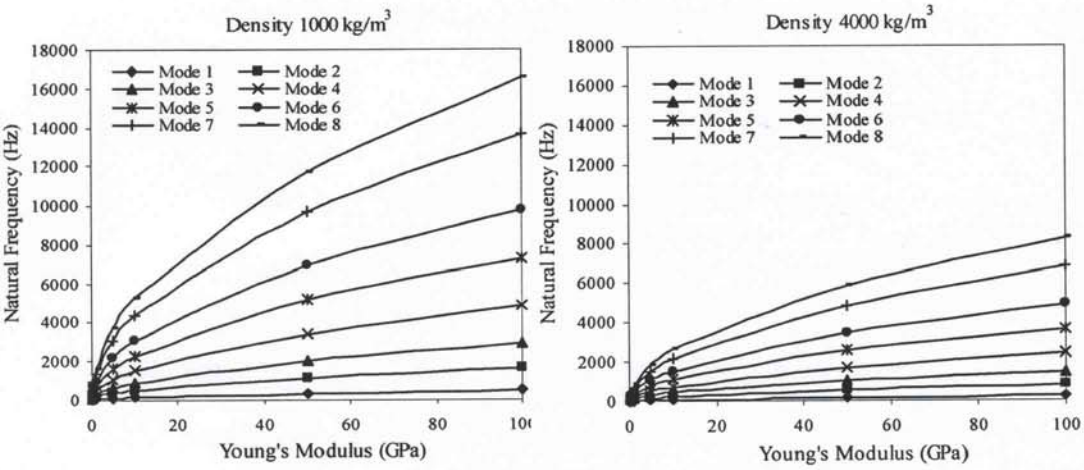

Fig. 7. Transverse natural frequencies versus Young's modulus of sheets

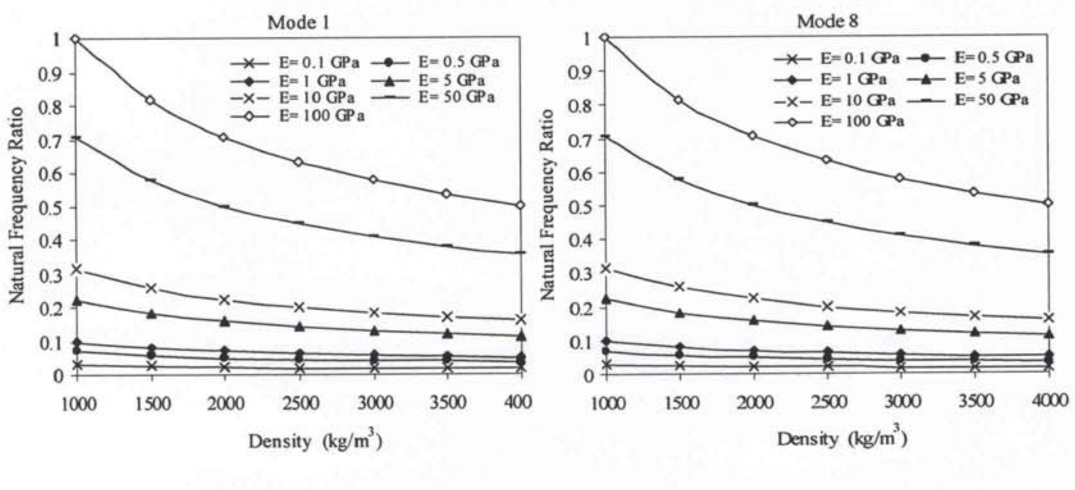

Fig. 8. Transverse natural frequency ratios versus densities of sheets

C. Effects of density of sheets.

Transverse natural frequencies versus Young's modulus of sheets with material densities D_s=1000 kg/m^3 and 4000 kg/m^3 is shown in fig. 7. The Poisson's ratio is 0.32, which is close to the Poisson's ratio of aluminum alloy. In the cases of material densities of 1500, 2000, 2500, 3000 and 3500 kg/m^3, similar variations of transverse natural frequency with Young's modulus of sheets as in the case of material densities D_s=1000 kg/m^3 and 4000 kg/m^3 are observed. For easy comparison, the transverse natural frequencies versus Young's modulus of sheets with material densities D_s=1000 kg/m^3 and 4000 kg/m^3 are drawn using the same co-ordinate scales. It is obvious that, in this case, the transverse natural frequencies decrease as the material densities of the sheet increase. Ranges to the first and eighth natural frequency ratios, caused by varying the material densities of the substrate material are shown in Fig. 8. In the cases of mode 2 to mode 7, similar variations of natural frequency ratios with material densities of sheets as in the case of mode 1 and mode 8 are observed. It can be seen from Fig. 8 that the natural frequency ratios of the transverse modes decrease as material densities of sheets increase.

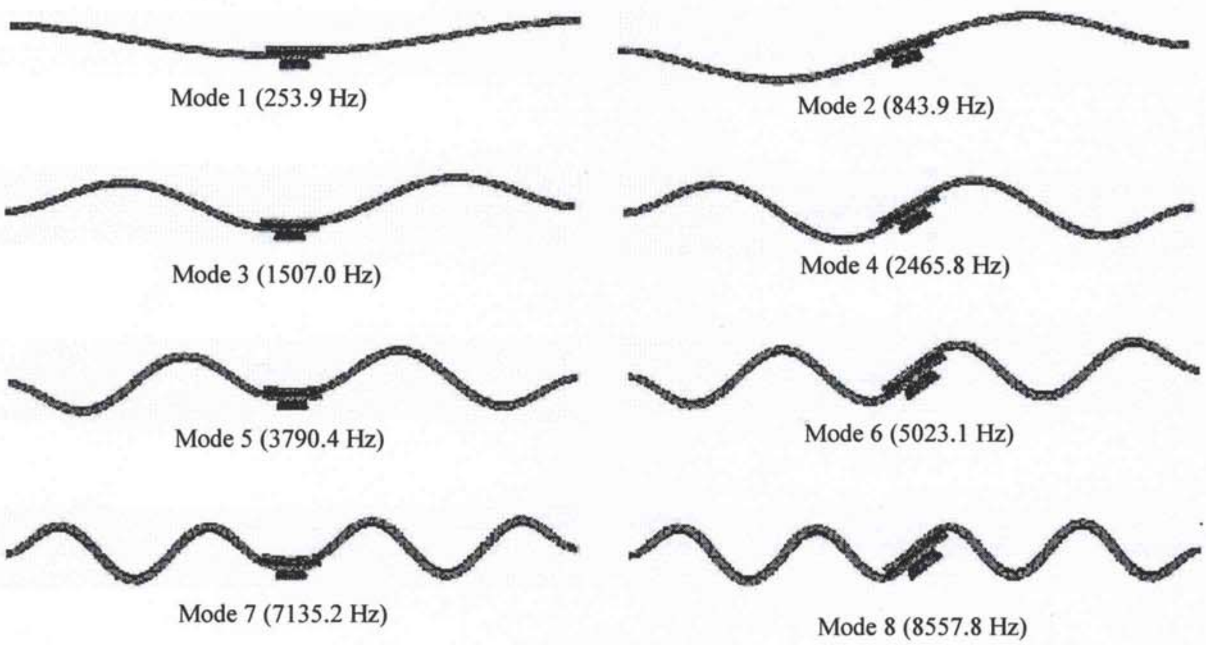

Fig. 9. First eight mode shapes of the single lap-jointed encastre clinched joint

V. Discussion of Mode Shapes

A great number of transverse mode shapes corresponding to different Young's modulus and Poisson's ratios of sheets were obtained from the parametric studies. However, the mode shapes were found to be similar throughout the test range and so only a few, typical mode shapes will be discussed in this paper. For ease of comparison, a reference beam was used for ease of comparison of mode shapes. The first eight mode shapes of the single lap-jointed encastre clinched joint corresponding to v_s=0.33, E_s=70 GPa and ρ=2700 kg/m^3 are shown in Fig. 9. It can be seen that the amplitudes of vibration at the mid-length of the joints are different for the odd and even modes. For the odd modes (1, 3, 5 and 7), symmetry is seen about the mid-length position. At these positions, the amplitudes of transverse free vibration are about equal to the peak amplitude. Thus, the geometry of the lap joint is very important and has a very significant effect on the dynamic response of the lap-jointed encastre clinched joints. Conversely, for the even modes 2, 4, 6 and 8, anti-symmetry is seen about the mid-length position and the amplitude of transverse free vibration at this position is approximately zero. Hence, variations in the structure of the lap joint have relatively less effect on the dynamic response of the lap-jointed encastre clinched joints.

VI. Conclusions

The free transverse vibration characteristics of single lap-jointed encastre clinched joints are investigated theoretically. The following conclusions can be drawn based on the results obtained from the present investigation:

The transverse natural frequencies of single lap jointed encastre clinched joints increase significantly as the Young's modulus of sheets increase, but only slightly change are encountered when the Poisson's ratio is varied.

The relationship between the natural frequencies and the Young's modulus of sheet is satisfactorily represented by an exponential curve.

The transverse natural frequencies of single lap jointed encastre clinched joints decrease as the material densities of the sheets increase. The natural frequency ratios of the transverse modes decrease as material densities of sheets increase.

REFERENCES

[1] X. He, I. Pearson and K. Young: "Review: Self-pierce riveting for sheet materials: State of the art", *J Mater. Process Technol*, 199(1-3), 27-36 (2008)

[2] S. Gao and L. Budde, "Mechanism of Mechanical Press Joining", *Int. J. Mach. Tools Manufact*. 34(5), 641-657 (1994)

[3] V. Hamel, J. M. Roelandt, J. N. Gacel and F. Schmit , "Finite element modeling of clinch forming with automatic remeshing", *Computers & Structures*, 77(2), 185-200 (2000)

[4] J. P. Varis, "The suitability of round clinching tools for high strength structural steel", *Thin-Walled Structures*, 40(3), 225-238 (2002)

[5] J. P. Varis, "Ensuring the integrity in clinching process", *J Mater. Process Technol*, 174(1-3), 277-285 (2006)

[6] R.F. Pedreschi and B.P. Sinha, "An experimental study of cold formed steel trusses using mechanical clinching", *Construction and Building Materials*, 22(5), 921-931 (2008)

[7]M. Carboni, S. Beretta and M. Monno, "Fatigue behaviour of tensile-shear loaded clinched joints", *Engineering Fracture Mechanics*, 73(2), 178-190 (2006)

[8] A.A. de Paula, M.T.P. Aguilar, A.E.M. Pertence and P.R. Cetlin, "Finite element simulations of the clinch joining of metallic sheets", *J Mater. Process Technol*, 182(1-3), 352-357 (2007)

[9] M. Oudjene and L. Ben-Ayed, "On the parametrical study of clinch joining of metallic sheets using the Taguchi method", *Engineering Structures*, 30(6), 1782-1788 (2008)

[10] M. Oudjene, L. Ben-Ayed, A. Delamézière and J.-L. Batoz, "Shape optimization of clinching tools using the response surface methodology with Moving Least-Square approximation", *J Mater. Process Technol*, 209, 289–296 (2009)

[11] X He and S.O.Oyadiji, "Influence of Adhesive Characteristics on the Transverse Free Vibration of Single Lap Jointed Cantilevered Beams", *J Mater. Process Technol,* 119:366-373 (2001)