Investigation of the Effect of V-Clamp Band Design Parameters on the Bending and Axial Stiffness of the Flanged Joints

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Abstract: The main target of this paper is to obtain an optimum wedge angle for best static and dynamic performance of a V-shaped clamp band separation mechanism. For this purpose, by using the finite element method, the proper 3D model for V-clamp band mechanism has been modelled and analysed in Abaqus/Explicit solver. In order to study the effect of wedge angle on bending and axial stiffness of V-clamp joint, many quasi-static analyses with different wedge angles were accomplished so the relation between wedge angle and axial stiffness of V-clamp joint under symmetric bending loading is extracted. In the next step, dynamic analyses were accomplished so the relation between wedge angle and separation time (duration between trigging moment and the time of disconnecting between flanges and wedged clamps) is extracted. For verification, this project results have been compared with the results of other researches and good agreement is observed. The results show that the optimal wedge angle for obtaining maximum stiffness together with minimum spring back disconnection time for the V-clamp band mechanism is 20˚.

Keywords: Flange, Static Loading & Separation, Stiffness, V-Clamp Band, Wedge

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1 INTRODUCTION

The wide application of V-clamp band systems in the aerospace is for a very stiff joint between two parts of the rocket or spacecraft until separation time with excellent structural properties. In V-clamp band systems (“Fig. 1”) from joint of two flanges, a section with “V” shape is created and then some wedges, connected by two belts, connect the flanges together. The separation of the belts is performed using the dynamic operation of separation mechanisms and the help of belt’s elastic property. Ares, Nanosat, Aryan and Soyuz are some examples of launch vehicles that have used V-clamp band separation system.

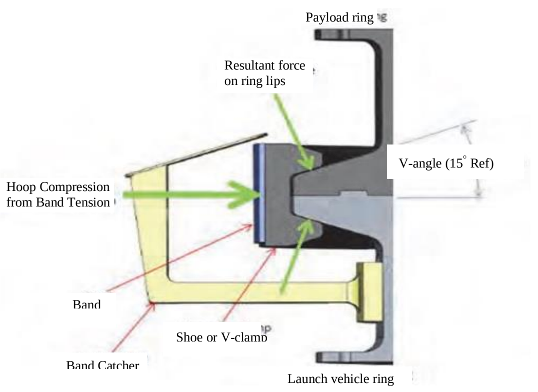


Fig. 1 V-clamp band system section.

The parameters affecting the bending and axial stiffness of joint section are as follows: Material of flange, belt and wedge, Belt section dimensions, Friction between wedge and flange, Clamp wedges and flanges angle, Amount of initial tension force of the belt. Some of advantages of joint with V-clamp band are high reliability, low shock and rapid dynamic performance with low disturbance during separation. Many references exist in the literature concerning about the static and dynamic mechanisms including V-clamp band. However, they investigated physical parameters and less attention is paid to the problem of optimization of V-clam band physical and geometrical parameters.

In this paper calculation of the relation between wedge angle and axial stiffness by means of quasi-static analyses with different wedge angles under symmetric bending loading is performed. Also calculation of the relation between separation time (duration between trigging time and the time of disconnecting between rings and wedges) and wedges angle by means of dynamic analysis is carried out. Accordingly, for the first time, optimum wedge angle for possible increased joint stiffness together with decreased separation time (joint disconnection duration) is obtained to be 20°. In “Figs. 2 to 4”, a general view of the location of the V-clamp band separation system in satellite and satellite launch vehicle, system assembly and its section are displayed.

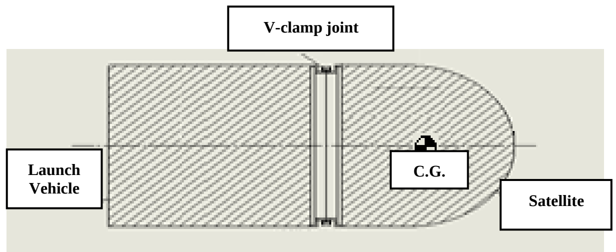


Fig. 2 General view of satellite and satellite launch vehicle connected together with V-clamp band separation system.

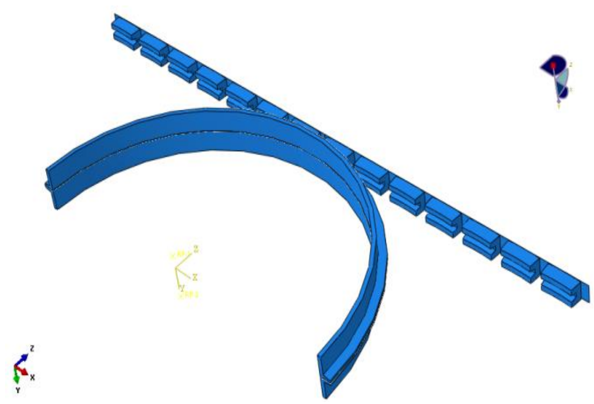


Fig. 3 V-clamp band separation system.

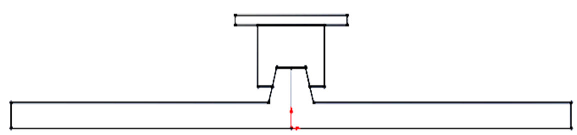


Fig. 4 Section of flanges and V-clamp band system.

2 LITERATURE REVIEW

Some of the most related researches, Refs. [1-14], and their solution methods are listed in “Table 1”. According to “Table 1”, among many researchers working of the topic of v-clamp bands, Qin and his co-workers have been performed the widest research including static, dynamic, vibration, shock and thermal analysis of the V-clamps. For example, Qin et al. developed a closed-form hysteresis model for the clamp band joint based on theoretical and numerical analyses of the interactions of the joint components. Then, they applied the hysteresis model to investigate the dynamic response of a payload fastened by the clamp band joint, where the nonlinearity and friction damping effects of the joint were evaluated

[2]. They also developed a dynamic model for the launching system incorporating the influence of the clamp band joint using the finite element method, where both of the launch vehicle and the spacecraft are modelled as Timoshenko beams [6]. They also developed an analytical model for the bending stiffness of the clamp band joint and then validated it by finite element analyses. They studied the bending behaviour of the clamp band joint using the proposed analytical model [7]. They studied the dynamic responses of the launch vehicle and spacecraft (LV/SC) system to the vibration and impact excitations, where the effect of the clamp band joint was taken into account [9]. They proposed a model representing the nonlinearity of the clamp band joint usable for convenient investigation of the effects of the structural and loading parameters on the dynamic characteristics of V-clamp joint system [10]. Among the investigated researches, no attempt has been observed for bi-objective optimization to achieve maximum stiffness together with minimum separation time for V-clamp band joints.

Table 1 Review of the researches in the literature

Row	Researcher (year)	Ref. No.	Research method		
			Analytical	Numerical	Experimental
1	Zhaoye Qin et al. (2016)	[1]	✓	✓	✓
2	Sahboun and Barrans (2015)	[2]	✓	✓	-
3	Delin Cui et al. (2015)	[3]	✓	✓	-
4	Barrans et al. (2014)	[4]	✓	✓	-
5	Junlan Li et al. (2014)	[5]	✓	✓	-
6	Qin et al. (2014)	[6]	-	✓	-
7	Qin et al. (2013)	[7]	✓	✓	-
8	Junland Li et al. (2012)	[8]	✓	-	-
9	Qin et al. (2011)	[9]	✓	✓	-
10	Qin et al. (2010)	[10]	✓	✓	✓
11	Jacob I. Rome et al. (2009)	[11]	-	✓	-
12	K Shoghi et al. (2003)	[12]	✓	-	-
13	Paul R.Klarer et al. (2002)	[13]	-	✓	-
14	M. Lanchop et al. (2000)	[14]	-	-	✓

Among the related works reviewed on the literature, to the best of the authors' knowledge, there is no research on the optimization of V-clamp bands considering its both static and dynamic behaviour. In this regard, in the present study, the optimization parameter is considered to be the wedge angle.

3 EXPRESSION OF THE PROBLEM

The objective function in this paper is as follows:
- Maximum joint stiffness in the flight
- Minimum disconnecting time of the belt from flanges, at the separation moment

Selected design variables include wedge angle and thickness of the belt. Baseline values of the structural parameters are according to "Table 1" in Ref. [7].

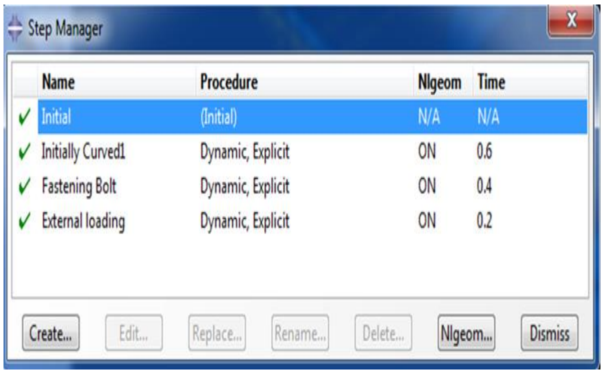
4 ANALYSIS METHOD USING FINITE ELEMENT ABAQUS SOFTWARE

With static analysis of V-clamp band, from start time until before separation moment of belt from flanges, with wedge angles of 10-30 degrees (with 5 degree increments) and dynamic analysis of separation moment of V-clamp band in wedge angles of 10-30 degrees (with 5 degree increments) can get diagrams for flanges or wedges. By comparing the two diagrams obtained from the static and dynamic analyses, one can obtain the optimal angle of the wedges or flanges.

For modelling in Abaqus, in the step module, for the quasi-static analysis of bending loading applied to the flanges ("Fig. 5"), three steps are defined:

Step 1: Bending the belt by applying a distributed pressure load ("Fig. 6")

Step 2: Applying the required force to simulate the fastening of the bolt (“Fig. 7”)
Step 3: Applying the loads due to the accelerations entering the centre of gravity of the satellite
At the stage of opening of the belts and separation of the belts and wedges from flanges, dynamic analysis (“Fig. 8”) is done so that the steps 1 and 2 are similar to the quasi-static analysis above, and the third step is as follows.
Step 4: This step is called the release step to open the belt.


Step Manager

	Name	Procedure	Nlgeom	Time
✓	Initial	(Initial)	N/A	N/A
✓	Initially Curved1	Dynamic, Explicit	ON	0.6
✓	Fastening Bolt	Dynamic, Explicit	ON	0.4
✓	External loading	Dynamic, Explicit	ON	0.2

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Fig. 5 Different steps in analysis time period at quasi-static analysis.

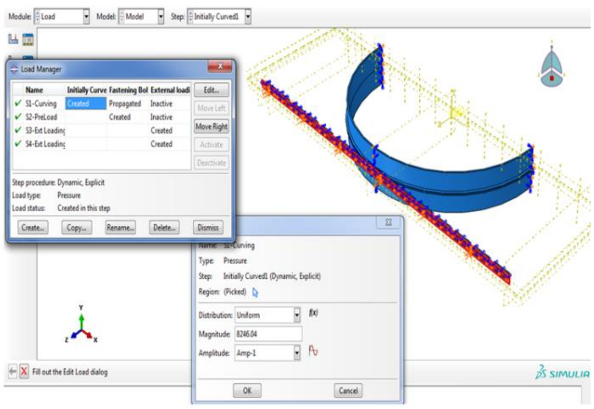


Fig. 6 Method of applying uniform pressure for bending the belt (step No.1).

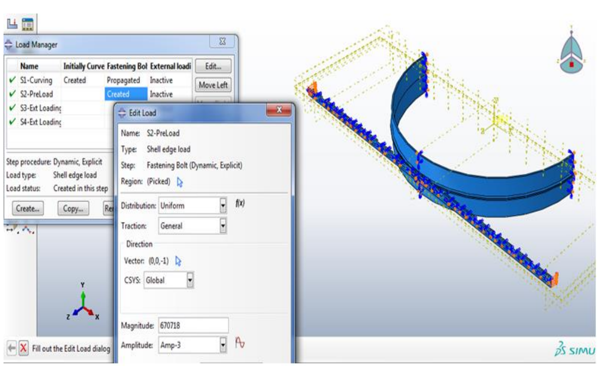
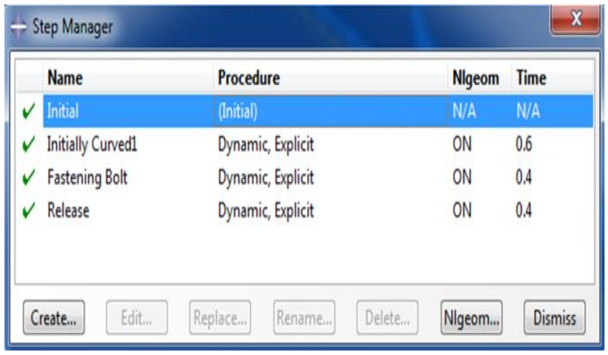


Fig. 7 Method of applying the required force to simulate the fastening of the explosive bolt (Step 2)**.**


Step Manager

	Name	Procedure	Nlgeom	Time
✓	Initial	(Initial)	N/A	N/A
✓	Initially Curved1	Dynamic, Explicit	ON	0.6
✓	Fastening Bolt	Dynamic, Explicit	ON	0.4
✓	Release	Dynamic, Explicit	ON	0.4

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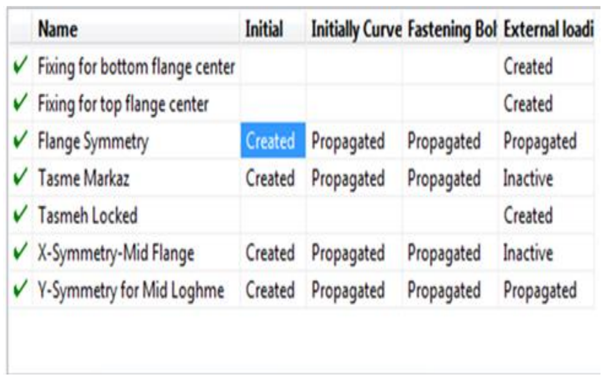
Fig. 8 Different steps in analysis time period at quasi-static analysis.

The boundary conditions for this analysis are applied according to “Fig. 9”.



	Name	Initial	Initially Curve	Fastening Bol	External loadi
✓	Fixing for bottom flange center				Created
✓	Fixing for top flange center				Created
✓	Flange Symmetry	Created	Propagated	Propagated	Propagated
✓	Tasme Markaz	Created	Propagated	Propagated	Inactive
✓	Tasmeh Locked				Created
✓	X-Symmetry-Mid Flange	Created	Propagated	Propagated	Inactive
✓	Y-Symmetry for Mid Loghme	Created	Propagated	Propagated	Propagated

Fig. 9 Applying the boundary conditions in different steps.

Mesh generated for belt and wedges after mesh sensitivity analysis of the results are shown in “Fig. 10”. In “Fig. 11”, the gap created between the two flanges, in the lower point of the section under tension, is indicated by numbers 1 and 2.
Criterion for evaluation of the bending stiffness of the joint is the ratio of the applied bending moment (to the joint section) to the distance (gap) created between points 1 and 2.

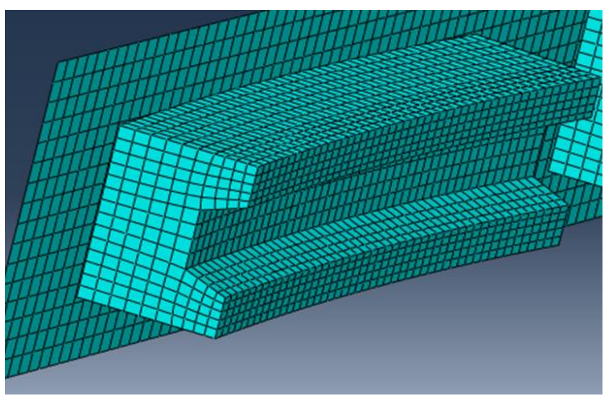


Fig. 10 Mesh generated for the part of the V-clamp band separation system.

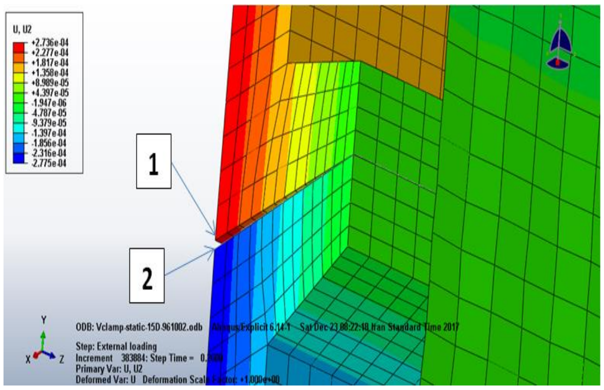


Fig. 11 Points 1 and 2 for calculating the stiffness.

5 RESULTS AND DISCUSSION

In “Table 2”, the results of the distance between separation system’s flanges, parallel to the central axis of the flanges, in static state for different wedge angles are shown. As can be seen in “Table 2”, by increasing the wedge angle, the gap between flanges is increased and hence the bending stiffness is decreased. In addition, in order to dimensionless results, each gap is divided by the average of the gaps.

Table 2 Distance between separation system’s flanges, parallel to the central axis of the flanges, in static solution for different angles

Row	Wedge angle [degree]	Gap between flanges [m]	Gap between flanges (dimensionless)
1	10	4.0537e-4	0.10985
2	15	5.40523e-4	0.14648
3	20	6.78731e-4	0.18393
4	25	9.59653e-4	0.26006
5	30	11.0584e-4	0.29968

In “Table 3”, a research reported by Qin et al. [7] is cited for validation purpose.

Table 3 Comparison of the gap (defined in Fig. 11) for various preloads and bending moments (wedge angle 15°)

Preload [kN]	Bending Moment [kN.m]	Gap between points 1 and 2 [mm]		Difference percentage
		Ref. [7] (Table 2)	Present work	
30	204	0.901	0.863	-4.22 %
40	272	1.2	1.28	+6.66 %

Due to good agreement between the analytical results in “Table 3” with the results of Ref. [7], the validity of the results of the present analyses is verified.

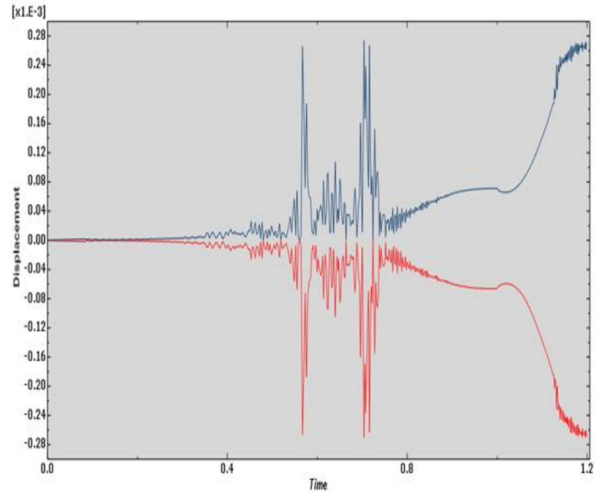


Fig. 12 The history of the distance between points 1 and 2 at different stages of static analysis in the wedge angle of 15 degrees.

According to the diagram in “Fig. 12”, time 0 to 0.6, is the closing step of the belt, time 0.6 to 1, is adjusted for the tension for closing and stiffening the belt and then time 1 to 1.2, is adjusted for the symmetric bending moment to the two sides of the joint. In “Fig. 13”, diagram of the area of contact surface between the inner surface of the wedges involved with the outer surface of the flanges at a 15 ° angle, from the start time of analysis to the moments after the separation, is shown. As can be seen, this area, immediately after the beginning of separation, is reduced to zero in a very short time.

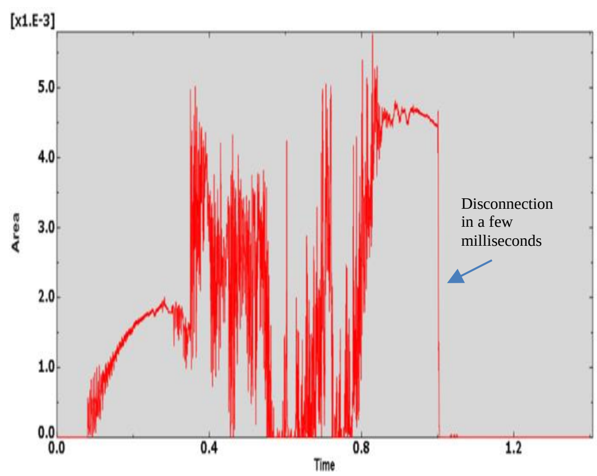


Fig. 13 Diagram of separation time of the wedges from flanges at wedge angle 15° in dynamic state.

In “Table 4”, the results of the separation time of wedges from the flanges, in different angles in dynamic mode, are shown. In addition, in order to obtain dimensionless results, each separation time is divided by the average of the separation times.

Table 4 The separation time of wedges from the flanges, in different angles in dynamic mode

Row	Wedge angle [Degree]	Time [msec]	The disconnecting time of wedges separation from flange in a dimensionless state
1	10	4.7	0.24227
2	15	4.4	0.22680
3	20	3.5	0.18041
4	25	3.4	0.17526
5	30	3.4	0.17526

In “Table 5”, the effect of changing the thickness of the belt in the constant width of the cross-section is studied on the separation time. The considered thicknesses for the cross-section of the belt are 1.2, 1.63, 2.0, 2.5 and 3.0 mm.

Table 5 Table of results of the separation time of wedges from the flanges, at 20° wedge angle in dynamic analysis and in different thicknesses of the belt

Row	Belt thickness [mm]	Time [msec]	The disconnecting time of wedges separation from flanges (dimensionless)
1	1.2	4	0.2381
2	1.63	3.5	0.2083
3	2.0	3.2	0.1905
4	2.5	3.1	0.1845
5	3.0	3	0.1786

According to “Table 5”, it can be concluded that by increasing the thickness of the belt, the separation time of the wedges from the flanges decreases, resulting in a better dynamic performance of the mechanism. In order to perform static and dynamic analysis of the V-clamp band separation system, two desktop computers with the following characteristics are used:

PC no. 1: core i7- 4790-3.6 GHz-RAM 16 GB
PC no. 2: core i7- 3930-3.2 GHz-RAM 24 GB

Also, for each analysis, depending on the complexity of boundary and force conditions, it takes about 70-80 hours.

6 OPTIMIZATION

After analysing the static and dynamic models of the V-clamp band separation mechanism, for different wedge angles and diagrams to be displayed, it is concluded that by decreasing the angle of the wedge in the static analysis, the bending stiffness of the joint increases and this is desirable. On the other hand, due to the dynamic analysis, by decreasing the angle of the wedge, the time of the dynamic separation of the mechanism increases, and this is undesirable.

Therefore, in order to find the best wedge angle for belt joint, in which angle, both the stiffness of the structure and separation time of the flanges are optimum. The diagram of separation time and flanges separation distance (gap) in the dimensionless state versus the wedge angle is shown in “Fig. 14”.

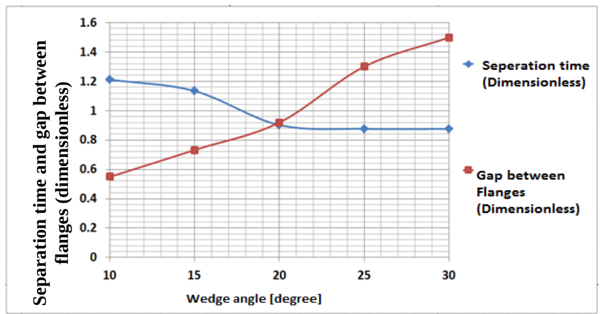


Fig. 14 The distance between the flanges and separation time versus the wedge angle.

The point of intersection of two graphs represents the optimal wedge angle. As can be seen in this figure, the two curves wedge angle across each other at about 20°. Therefore, 20° wedge angle, is the optimal wedge angle.

7 CONCLUSION

For the first time, the optimum wedge angle for best static and dynamic performance of a V-shaped clamp band separation mechanism is extracted. The finite element method is applied by making a 3D model for V-clamp band mechanism using Abaqus/Explicit solver. The main outcomes of the present research are listed as follows:

- The wedge angle is an important design parameter affecting the static bending and axial stiffness of V-clamp band.
- The effect of wedge angle on the bending and axial stiffness of V-clamp band is more than its effect on the separation time.
- By increasing the value of wedge angle, both the bending and axial stiffness and separation time are decreased.
- The optimal wedge angle for obtaining maximum stiffness together with minimum spring back disconnection (separation) time for the considered V-clamp band mechanism is 20˚.

REFERENCES

[1] Qin, Z., Cui, D., Yan, S., and Chu, F., Hysteresis Modeling of Clamp Band Joint with Macro-Slip, Mechanical Systems and Signal Processing, Vol. 66, 2016, pp. 89-110.

[2] Sahboun, S. M., Barrans, S. M., Simulating Torsional Slip in V-band Clamp Joints, Applied Mechanics and Materials, Vol. 798, 2015, pp. 53-58.

[3] Cui, D., Yan, S., Li, J., Qin, Z., and Guo, X., Dynamic Analysis of Satellite Separation Considering the Flexibility of Interface Rings, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol. 229, No. 10, 2015, pp. 1886-1902.

[4] Barrans, S. M., Khodabakhshi, G., and Muller, M., Classical and Numerical Approaches to Determining V-Section Band Clamp Axial Stiffness, Open Engineering, Vol. 5, No. 1, 2014, pp. 99-110.

[5] Li, J., Yan, S., and Tan, X., Dynamic-Envelope Analysis of Clamp-Band Joint Considering Pyroshock of Satellite Separation, Journal of Spacecraft and Rockets, Vol. 51, No. 5, 2014, pp. 1390-1400.

[6] Qin, Z. Y., Yan, S. Z., and Chu, F. L., Influence of Clamp Band Joint On Dynamic Behavior of Launching System in Ascent Flight, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol. 228, No. 1, 2014, pp. 97-114.

[7] Qin, Z. Y., Yan, S. Z., and Chu, F. L., Analytical Modeling of Clamp Band Joint Under External Bending Moment, Aerospace Science and Technology, Vol. 25, No. 1, 2013, pp. 45-55.

[8] Li, J. L., Yan, S. Z., and Tan, X. F., Modeling and Simulation of Clamp Band Dynamic Envelope in a LV/SC Separation System, Applied Mechanics and Materials, Vol. 141, 2012, pp. 359-363.

[9] Qin, Z. Y., Yan, S. Z., and Chu, F. L., Dynamic Characteristics of Launch Vehicle and Spacecraft Connected by Clamp Band, Journal of Sound and Vibration, Vol. 330, No. 10, 2011, pp. 2161-2173.

[10] Qin, Z. Y., Yan, S. Z., and Chu, F. L., Dynamic Analysis of Clamp Band Joint System Subjected to Axial Vibration, Journal of sound and vibration, Vol. 329, No. 21, 2010, pp. 4486-4500.

[11] Rome, J., Goyal, V., and Martino, N., Techniques for Finite Element Analysis of Clamp Band Systems, In 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 17th AIAA/ASME/AHS Adaptive Structures Conference 11th AIAA No, 2009, pp. 2353.

[12] Shoghi, K., Rao, H. V., and Barrans, S. M., Stress in A Flat Section Band Clamp, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 217, No. 7, 2003, pp. 821-830.

[13] Klarer, P. R., Vaughn, M. R., Gilbride, J. F., Baty, R. S., and Adams, J. L., Design for an Internal Circular Compression Band Restraint Device (Marman Clamp, V-Band). Sandia national Laboratories, SAND2002-2744J, 2002.

[14] Lancho, M., Larrauri, J., and Gomez-Molinero, V., CRSS: A Separation System for Launching Very Heavy Payloads, Acta Astronautica, Vol. 47, No. 2-9, 2000, pp. 153-162.