

Pre-Stressed Modal Analysis of the Elastic Rail Clip - MARK-III – T3701

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Abstract - In the Industry, the Modal Analysis or Natural Frequency Analysis or Eigenvalue Solution of the Structures is most widely accepted to avoid the resonance of the Structure (Component / Assembly). Finding the Mode Shapes of the Structure is also a prime importance. When the Structure is excited with the Frequencies which are very close to the Natural Frequencies may lead to catastrophic failure of the structure. Apart from this, many structures are designed to work under Stress. When performing the Modal Analysis on such Structures, the Pre-Stressed Effect must be considered, because the Stress State Changes the Natural Frequency of the Structure. The Response of the Structure without the Pre-Stress Effect may be very different from the Response of the Structure with the Pre-Stress Effect. The Differential Stiffness [adding a Stress Stiffness Matrix – may be due to Linear or Non-Linear] is considered while finding out the Eigenvalue Solution. Both Free-Free and Pre-Stressed Modal Analysis results in Natural Frequencies and Mode Shapes but under different conditions. If Pre-Stressed Modal results differ appreciably from design intent, one must understand which parameters are causing this change in modal results and must be optimized accordingly. The Elastic Rail Clip (ERC – MARK-III – T3701) is studied for the Pre-Stressed Effect and its effect on the Mode Shapes and the Natural Frequencies. The Frequencies and Mode Shapes of Pre-Stressed Modal Analysis differ than the Free-Free Modal Analysis due to the effect of Differential Stiffness comes into the picture when the ERC in situ.

Keywords: Pre-Stressed Modal Analysis, Rail Fastening System, Elastic Rail Clip, ERC.

I. INTRODUCTION

The structure of the Railway Track consists of (i) Super-Structure – the Rail, Fastening System and Sleepers; (ii) Sub-Structure – Non-Cohesive Granular Materials viz. Stone Ballast. Primary functions of the Fastening Systems are suppressing the vibrations due to traffic impact and preserving the transverse slope and the gauge. Spring Clips classified based on Flexibility can be Rigid and Elastic. Rail Fastening Systems consist of Rail, Elastic Rail Clip, Liner, and Rubber Pad as shown in the Fig 1.1.



Figure 1.1 A schematic of Rail Track and Rail Fastening System

The essential functions of an Elastic Rail Clip / Tension-Clamp are to provide adequate Toe-Load or Clamping Force on the Rail to ensure that the Rail continues to remain in contact with the Rail-Pad under all Static and Dynamic conditions. This paper is related to Elastic Rail Clip (ERC-Mark – III T-3701) which falls under Pandrol Fastening System used in Indian Railways. The Clips are manufactured from Rolled Silicon-Manganese Spring Steel rounds conforming to Grade 55 Si7 of IS: 3195-1992. The Clips are hot formed and are subsequently oil Hardened and Tempered to give uniform hardness across the section. The Indian Railway's Standard Specification for Elastic Rail- Clips, S. No. T-31-1992 stipulates among other things the quality of raw materials, the technical requirements, the inspection, and testing procedures for the different designs of ERC.

II. LITERATURE SURVEY

S.V. Shinde, et al. [1], studied the Rail Fastening System and its different components. We found references to the various sources for relationship between the applied loads and stress on the rail clip, established in laboratory tests for design of elastic rail clip. It also states that, the Elastic Rail Clip – ERC behaves non-linearly under its operating range of 850 Kg to 1100 Kg load and with different loading conditions, Elastic Rail Clip – ERC demonstrate the non-linear behaviour. The model of ERC is analysed in Ansys; it has two boundary conditions: The 1st Case considers the Fixed Support at Centre Leg, and Fixed Support at the Heel, Force as a load on the Toe, and the 2nd Case considers the Fixed Support at Centre Leg, and Fixed Support at the Toe, Force as a load on the Heel. Xiao Hong, et al. [2], discuss the use of Analysis results show that the insertion depth and the clip deflection are the important parameters to the Fatigue Behaviour of the e-clip. The mismatch of the two parameters may cause the fracture of the e-clip. The e-clips are optimized by the Fatigue Life Analysis and the Energy Analysis. The suggestions are that the clip deflection should be within 10 mm to 12 mm, and the gap from rear arch to cast shoulder should be within 3 mm to 9 mm. The calculation results have a good correlation with the field observation, which validates the analysing method.

Mohammadzadeh et. al. [3], presented stress-based approach to develop comprehensive method for fatigue reliability analysis of the fastening spring clip. The Axle load, speed, and material properties are assumed to be random variables. From the dynamic analysis of the track and trains, the load in terms of the displacement time histories is applied to fastening clips. Using the Miler's Rule and Monte Carlo Simulation, the reliability and sensitivities are plotted. It further concluded that the stress range and material parameters have significant effect on the fatigue crack.

Jaroslav Smutny et al. [4], presented that based on measurements and analyses, makes it possible to state that the methods presented above are very good for the measurement of dynamic acoustic parameters of rail fastenings. The use of these methods enables the testing of new types of rail fastenings and different types of rail washers under rails and the opportunity to optimise the geometric location of damping elements on rail, etc. From the mathematical means of signal analysis, it is possible to utilise both linear and non-linear time frequency procedures for time-localisation of the occurrence of frequency elements of stationary and non-stationary signals.

Zhao et al. [5] analysed the influence of fastening model on the high frequency dynamic contact forces at singular rail surface defects.

III. STATIC ANALYSIS OF ERC USING CASTIGLIANO THEOREM

This paper demonstrates the theoretical calculations based on Static Structural Analysis using the Castigliano's Theorem for the Elastic Rail Clip Mark-III – T3701 – Referenced by RDSO.

Castigliano Theorem:

To solve the given problem of cantilever beam we are using Castigliano’s Theorem to find out the deflection at certain point on a clip. The Castigliano's Theorem can also be applied to angular rotations under the action of bending moments or torques. For the bending application the theorem states that:

“If the total strain energy, expressed in terms of the external moments, be partially differentiated with respect to one of the moments, the result is the angular deflection (in radians) of the point of application of that moment and in its direction”

The Deflection – Force Relations are obtained using Castigliano's Theorem.

Castigliano’s Theorem for Beam Deflection:

For Linearly Elastic Structures, the partial derivative of the Strain Energy with respect to an Applied Force (or Couple) is equal to the Displacement (or Rotation) of the Force (or Couple) along its Line of Action. Where δ is the deflection at the point of application of force P, θ is the rotation at the point of application of the couple M, and U is the strain energy. The strain energy of a beam was known to be

$$U = \int_0^L \frac{M^2}{2EI} dx$$

Finding the partial derivative of this expression will give us the equations of Castigliano’s Deflection and Rotation of Beams. The equations are written below for convenience.

$$\delta = \frac{\partial U}{\partial P} \qquad \delta = \frac{\partial}{\partial P} \int_0^L \frac{M^2(x)}{2EI} dx = \frac{\partial}{\partial P} \int_0^L \frac{(Px)^2}{2EI} dx$$

$$\delta = \int_0^L \frac{Px^2}{EI} dx = \frac{PL^3}{3EI}$$

Theoretical Calculations:

Load on ERC	P	1000	N
Length of ERC	L1	357.35	mm
Segment of ERC	L	35.735	mm
Young’s Modulus	E	2.00E+05	MPa
Area moment of Inertia	I	961.93	kg/mm ²

1000 (N) x 35.7353 (mm³)

deflection = δ = 0.079 mm

3 x 2.0e5 (MPa) x 961.93 (

By using Flexural Formula,

$$M = E \sigma$$

I R y

$$\sigma_{\max} = 29.35 \text{ N/mm}^2$$

Segment	Length	Moment	Deflection (mm)		Stress (N/mm ²)	
			Theoretical	Analytical	Theoretical	Analytical
1	3.57	3570	7.883E-05	0	0.029279	-24.799
2	7.14	7140	0.0006307	0.009295	0.23423	-18.901
3	10.71	10710	0.0021285	0.01859	0.790525	-13.002
4	14.28	14280	0.0050453	0.027885	1.873837	-7.1038
5	17.85	17850	0.0098542	0.03718	3.659838	-1.2052
6	21.42	21420	0.017028	0.046474	6.3242	4.6933
7	24.99	24990	0.0270398	0.055769	10.04259	10.592
8	28.56	28560	0.0403627	0.065064	14.9907	16.49
9	32.13	32130	0.0574695	0.074359	21.34417	22.389
10	35.73	35730	0.0790322	0.083654	29.35258	28.288

Table 1: Calculation Table for Deflection of ERC at all Segments

The Analytical Results are compared against the Theoretical Results and error is calculated.

Result Type	Theoretical	Analytical	Percentage Error
Total Deformation (mm)	0.079	0.084	5.59%
Normal Stress (N/mm ²)	29.35	28.29	3.74%

Table 2: Percentage Error in Results

IV. PRE-STRESSED MODAL ANALYSIS OF ERC:

Vibration Analysis of the beam components is extremely helpful in Engineering Analysis and Design. Experimental Modal Analysis is the process to determine the Modal Parameters like Natural Frequency, Mode Shape, and Damping. This paper presents Numerical Modal Analysis of beam in Free-Free and Simply Supported Boundary Condition. It is believed that the Stress Stiffening can change the Response Frequencies of a System which impacts both Modal and Transient Dynamic Responses of the System. Natural Frequency is the property of any Material and it depends on the Stiffness as well as the applied damping. Both Free-Free Modal and Pre-Stressed Modal results are Natural Frequencies but under different conditions.

The Pre-Stress Modal Analysis of Thin-Walled Pressure Vessels where the Pressurization dominates Stiffness and hence, the Natural Frequencies. Similarly, the applications like Rocket Fuel Tanks and Satellite Oxygen Tanks, Structures subject to significant Dead Weight Loading, such as Suspension Cable Bridges and Oil Tankers, Tensioning of Strings in Musical Instruments to achieve required Frequencies, Structures subject to Centrifugal Loading such as Jet Engine Turbine and Fan Blades involve Pre-Stress Modal Analysis due to the nature of the loading conditions.

The objective of applying a Static Load to a Structure during a normal modes analysis is to use the loaded structure in obtaining the Stiffness Matrix for the Modal Analysis.

The eigen value problem equation corresponding to pre-stiffened structures is:

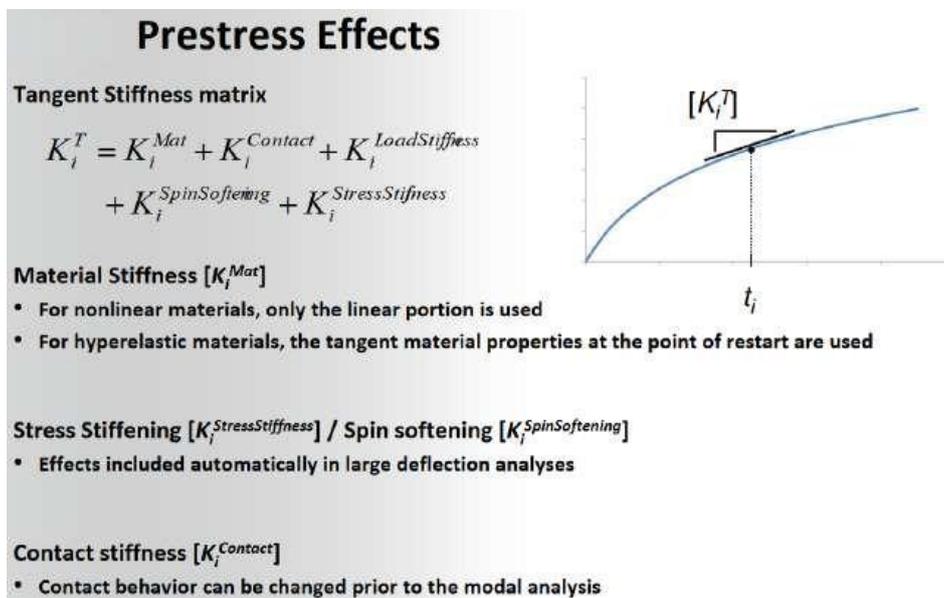
$$(-\omega^2[M] + ([K] + [K]_D))\{\phi\} = \{0\}$$

where $[K]_D$ is the differential stiffness matrix resulting from the applied load.

In general, there are three terms/effects that can influence the **Stiffness Matrix**:

1. Material Non-Linearity, e.g. elastic-plastic behaviour
2. Geometric Stiffness, due to changes in the Structural Shape... these can be due to Small or Large Displacement behaviour.
3. Follower-Force Stiffness, arising as the loading changes its line of action relative to the Displacements... these can be due to Small or Large Displacement behaviour.

Since the Normal Modes Analysis is Linear, only the Geometric and Follower Force Stiffness changes due to Small Displacements will be considered. For incorporating the Full Non-Linear Effects of the Loading, a Non-Linear Static Solution is required. A pictorial Pre-Stress Effect in terms of the Stiffness is mentioned below:



This is explained by the fact that the stress state would influence the values of the stiffness matrix. In this contribution, it is intended to investigate the effect of Pre-stress on the Vibration Behaviour of simple structures using Finite Element Tool – ANSYS. This is achieved by first performing a Structural Analysis on a loaded structure then make us of the resulting stress field to proceed on a Modal Analysis.

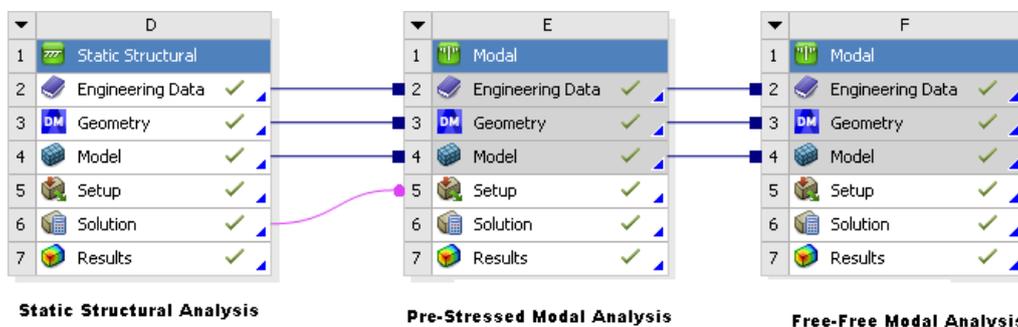


Figure 4.1 Schematic of Pre-Stressed Analysis

The 3-D Model (Finite Element Model) of ERC is meshed using SOLID 186 Element which is 20- Node Structural Solid Element, consists of 1020 Number of Elements and 4980 Number of Nodes.

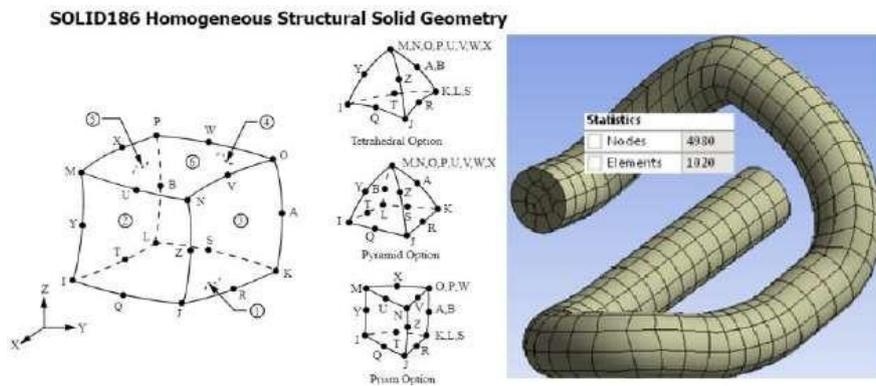


Figure 4.2 SOLID 186 Element and FE Model of ERC

The Figure 4.3 depicts the Modal Analysis using ANSYS Software, and its results in Free-Free Condition.

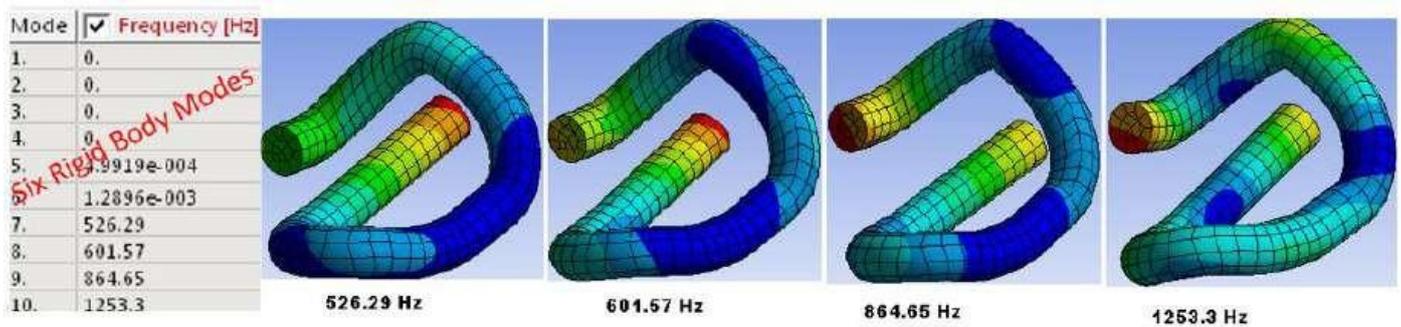


Figure 4.3 Frequencies and Mode Shapes of Free-Free Modal Analysis of ERC

The Pre-Stressed Modal Analysis used to calculate Modal Characteristics of a Pre-Stressed Structure, It uses the results from a Static Structural Analysis performed in ANSYS to calculate the Natural Frequencies and Mode Shapes of the model. It essentially uses the Differential Stiffness (which is obtained from the Static Structural Analysis) in the subsequent Modal Analysis.

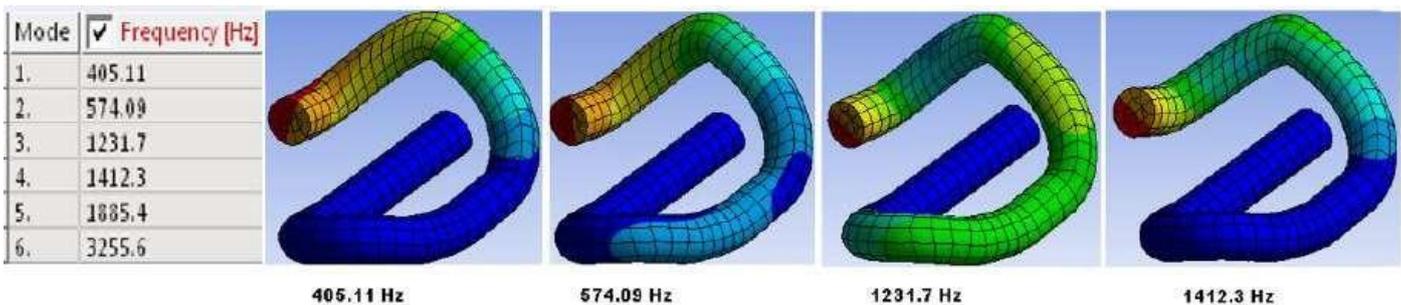


Figure 4.4 Frequencies and Mode Shapes of Pre-Stressed Modal Analysis of ERC

V. RESULTS, VALIDATION AND CONCLUSION:

This paper studies the Elastic Rail Clip (ERC – MARK-III – T3701, used in Indian Railways) is studied for the Pre-Stressed Effect and its effect on the Mode Shapes and the Natural Frequencies. The Frequencies and Mode Shapes of Pre-Stressed Modal Analysis differ than the Free- Free Modal Analysis due to the effect of Differential Stiffness comes into the picture when the ERC in situ. It presents the Numerical Modal Analysis in Free-Free and Simply Supported Boundary Condition. It is believed that the Stress Stiffening can change the Response Frequencies of a System. Because of the Stress State Changes in the ERC; the Natural Frequency changes and the Response of the Structure without the Pre-Stress Effect is very different from the Response of the

Structure with the Pre-Stress Effect. The Differential Stiffness [adding a Stress Stiffness Matrix – may be due to Linear or Non-Linear] is considered while finding out the Eigenvalue Solution. Following are the conclusion drawn from this paper:

- 1) In Static Structural Analysis, the Theoretical Value of Total Deformation is within the limits of 6% of Analytical Value.
- 2) In Static Structural Analysis, the Theoretical Value of Normal Stress is within the limits of 4% of Analytical Value.
- 3) The components with the prescribed boundary conditions in Pre-Stressed Analysis the Frequencies observed are 1) 405.11 Hz, 2) 574.09 Hz, 3) 1231.7 Hz, 4) 1412.3 Hz whereas with the Modal Analysis (Free – Free) with no boundary conditions the Frequencies observed are 1) 526.29 Hz, 2) 601.57 Hz, 3) 864.65 Hz, 4) 1253.3 Hz.
- 4) The Frequencies and Mode Shapes of Pre-Stressed Modal Analysis differ than the Free-Free Modal Analysis due to the effect of Differential Stiffness.
- 5) The Modal Analysis calculates Natural Frequencies and Mode Shapes of the Structure. Participation Factor shows the most prominent modes in a certain direction that will be excited by forces in that direction. Effective Mass can be useful for confirming that enough have been extracted for further analysis.
- 6) The Pre-Stressed Modal Analysis accounts the Stresses in a part can impact its Stiffness due to Stress Stiffening. Pre-Stressed Modal Analysis is used to calculate Modal Characteristics of a Pre-Stressed Structure. Base Static/Transient Stress Analysis is followed by Modal analysis using Linear Perturbation Technique. Base Static Stress Analysis can be Linear/Non-Linear but Modal Analysis is Linear.

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