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RESEARCH ARTICLE

SUITABILITY OFALUMINIUM ALLOY DECKS ON STEEL GIRDERS IN HORIZONTALLY CURVED BRIDGES.

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Abstract

A finite element analysis of horizontally curved aluminium bridge deck of $\theta \leq 34.4$ is presented in this study. The structural behaviour of deck was studied while varying applied normal and centrifugal stresses at various geometric properties. The applied normal and centrifugal stresses represents that obtained under service conditions when the deck is subjected to dead (e.g. deck self-weight, filling, parapet, etc.) and live loads (e.g. wheel loads). The results obtained showed that the maximum Von Mises stresses decreases with increasing thickness of stiffeners. A minimum stiffener thickness of 7mm is found to be ideal in withstanding the applied stresses. The maximum Von Mises stresses obtained was less than the Yield stress of the materialthus suggesting that the proprietary Alumadeck^{TM} is suitable for use as bridge deck in curved alignments.

Introduction:-

The majority of bridge decks today are in deplorable conditions(Hadipriono, 1985). The conventional highway bridge deck system deteriorates over time as a result of changes in microclimate such as changes in temperature, moisture content fluctuation and freeze-thaw cycle. Corrosion of the reinforcing steel has been identified as the major cause of the deterioration in concrete therefore it is the most important factor responsible for the large majority of structurally deficient bridges (Siwowski, 2006).

Bridge decks require major repair or replacement every 15-20 years while the substructure and super structure tends to last 40 years or more (Wesley and John, 2006). Eventually, some-day the bridge deck will need to be replaced. This has spirited the search for alternative decks that can resist environmental factors without any protective coating (Davis, 1993), reduce highway closure time and make retrofitting that meet the current design specifications possible while retaining the super structure and substructure.

Background of study:-

This work investigates using Finite Element Analysis as packaged in ABAQUS to ascertain the suitability of use of the proposed curved aluminium alloy deck (Alumadeck^{TM}) under wheel loads in horizontally curved alignments on steel girders.

Improving the life of bridges can be achieved using alternative materials, such as fiber reinforced composites or aluminum. Since composites and aluminum are: lighter than steel and concrete, do not rust nor need painting or protective coatings, and have shorter fabrication as well as erection time; thus cheaper, they have distinct advantage over other construction materials (Siwowski, 2006). Aluminium will often be cheaper than concrete when whole-life costs are calculated (Tindall, 2008; Dwight, 1999). The suggestion made by Reynolds AluminiumCompany (manufacturers of the Alumadeck^{TM}) has given way to a feasible alternative to conventional reinforced concrete decks (Dobmeier et al., 2001). This deck is new and requires a close study of its characteristic structural behavior.

The modern transportation industry encounters an increasing use of curved and skewed I-girder/ beam bridges for a number of reasons. These types of bridges are becoming more common as highway infrastructure is increasingly rebuilt atop existing structures to handle increasing traffic volumes or new interchange geometries within the context of urban settings (Ozgur, 2007; Linzell, et al., 2010). They are particularly advantageous for construction of roadways in areas that have serious geographical or manmade impediments (Lydzinski and Baber, 2008).

Due to the need to augment the traffic capacity of urban highways, restrictions on existing land use, and consideration of aesthetics, there has been a steady growth in the use of curved steel bridges in the past twenty-five years. Increasingly complex interchanges and the desire to conform to existing terrain have made curved bridges more attractive (Brett, et al., 2000).

The response of bridges to dynamic vehicular loading is important to bridge evaluation. A bridge's strength, rating, and serviceability depend on the manner upon which the bridge behaves under dynamic loads. Typically, analysis for vehicle- and wind-induced vibration is not to be considered in the bridge design. Although a vehicle crossing a bridge is not a static situation, the bridge is analyzed by statically placing the vehicle at various locations along the bridge and applying a dynamic load allowance as stated in AASHTO Specifications.

Recent studies carried out by the Virginia Transportation Research Council to evaluate two Reynolds aluminum deck systems gave results which demonstrated that aluminium bridge decks are a feasible alternative to reinforced concrete decks from the standpoint of strength and serviceability. Safety level studies carried out on straight girders by Agboola et al, (2010), also demonstrated the superiority of aluminium decks over conventional concrete decks on steel girders for straight bridges.

Research carried out by AASHTO LRFD (2004), Road Research (1979) and the BS5400 (1990), have shown the types of loadings that act on bridges. According to Road Research (1979), the load carrying capacity of bridges must meet two safety criteria namely: unrestricted use by vehicles and restricted use by heavier vehicles. Two types of loads are considered in the design of bridges. First are the permanent loads known as the dead load, superimposed dead loads, loads due to filling materials, differential settlement as well as loads due to creep and shrinkage. Dead load carried by a bridge member consists of its own weight and the portions of the weight of the superstructure and any fixed loads supported by the member. Secondly are transient loads defined as wind loads, temperature loads, exceptional loads, erection loads, centrifugal loads, braking, skidding and collision loads. The loadings used in this analysis are classified into dead loads and imposed loads. The imposed/ live load used is the HL-93 loading (AASHTO, 2004).

There are lots of different aluminium alloys available, and each of these in diverse tempers or heat treatments, such that their groupings run into hundreds (Mazzolani, 2006). The Aluminium bridge deck used in this study is fabricated from the 6063-T6 aluminum.In this presentation, the proposed aluminium bridge deck is evaluated for system II stresses only. This is represented by the transverse bending of the top deck flanges between girders due to applied loads.

Materials and methods:-

Theory of Curved Plates:-

According toTimoshenko and Woinowsky(1982) and, Hiens and Hails (1969), the differential equation for flexure of a curved plate is given as;

$$D_r \frac{\partial^4 \eta}{\partial r^4} + 2H \frac{\partial^4 \eta}{r^2 \partial r^2 \partial \theta^2} + D_\theta \frac{\partial^4 \eta}{r^4 \partial \theta^4} + 2D_r \frac{\partial^3 \eta}{r \partial r^3} - 2H \frac{\partial^3 \eta}{r^3 \partial r \partial \theta^2} - D_\theta \frac{\partial^2 \eta}{r \partial r^2} + 2(D_\theta + H) \frac{\partial^2 \eta}{r^4 \partial \theta^4} + D_\theta \frac{\partial \eta}{\partial r^3 \partial r} = q \quad (1)$$

Where the parameters D_r, D_θ and H are the stiffness parameters expressed as

$$D_r = \frac{Et^3 r}{[12(1-\mu^2)]} \quad (2)$$

$$D_\theta = \frac{Et^3 r}{[12(1-\mu^2)]} \quad (3)$$

$$H = GK_1 \quad (4)$$

$$D_{r\theta} = H/2$$

Where P = Loading, r = Radius of bridge, E = Modulus of elasticity, K_1 = Torsional Constant, μ = Poison Constant, t = Thickness of Deck, r = Unit Radius of Deck, G = Modulus of Rigidity.
θ = Angle subtended by section; η = Deflection of the section; q = Uniformly Distributed load; $D_{r\theta}$ = Torsional rigidity; D_r = Flexural rigidity in the r-direction; D_θ = Flexural rigidity in the θ direction.

The general solution to Equation (1) determined by Heins and Hails (1975) is

$$\eta = \sum[AX^{m1} + BX^{m2} + CX^{m3} + DX^{m4}]\sin\lambda\theta + \frac{4pr^4 \sin\lambda\theta}{D_r n\pi[72-18\beta\lambda^2-\alpha(8+2\lambda^2-\lambda^4)]} \quad (5)$$

$$\alpha = \frac{D_\theta}{D_r} = 1, \beta = \frac{H}{D_r} = 0.98, \lambda = \frac{n\pi}{\theta} = 0.37, X = \frac{r_i}{r}$$

In which the four roots of the equations m_1, m_2, m_3, and m_4 can be expressed as;

$$m_1, m_2, m_3, m_4 = \pm\left\{(\alpha + 2\beta\lambda^2 + 1)/2 \pm \left[0.25(1+\alpha^2\beta^2)^2 - (\lambda^2-1)^2\alpha\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}} + 1$$

Where for the above equation, $X = \frac{r}{r_\theta}$,
r = Radius at the point of consideration,
r_θ = Radius of the bridge deck system

The curved plate moment Differential Equations are as follows;

$$M_r = -D_r \frac{\partial^2\eta}{\partial r^2} \text{ (Radial Moment)} \quad (6)$$

$$M_\theta = -D_r \frac{\partial\eta}{\partial r} + \frac{\partial^2\eta}{r^2\,\partial\theta^2} \text{ (Angular Moment)} \quad (7)$$

$$R_r = \left[\left(\frac{\partial^3\eta}{\partial r^3} + \frac{\partial^2\eta}{\partial r^2}\right) + 2\frac{H}{D_r}\left(\frac{\partial^3\eta}{r^3\,\partial r\,\partial\theta^2} - \frac{\partial^2\eta}{r^3\,\partial\theta^2}\right) - \frac{D_\theta}{D_r}\left(\frac{\partial\eta}{r^3\,\partial r} + \frac{\partial^2\eta}{r^3\,\partial\theta^2}\right)\right] \text{ (Radial Shear)} \quad (8)$$

$$R_\theta = -D_\theta\left[\left(\frac{\partial^2\eta}{r^2\,\partial r\,\partial\eta} + \frac{\partial^3\eta}{r^3\,\partial r\,\partial\theta}\right) + 2\frac{H}{D_\theta}\left(\frac{\partial^2\eta}{r^2\,\partial r\,\partial\theta} + \frac{\partial^2\eta}{r^2\,\partial r\,\partial\theta} + \frac{\partial\eta}{r^3\,\partial r}\right)\right] \text{ (Angular shear)} \quad (9)$$

Equations (6) and (7) are expressed in terms of the general solution of equation (5), for the radial moment and radial shear. Since the angular moment and shear are much smaller than the radial moment and shear, the angular moment and shear shall be neglected. Thus,

$$-M_r\frac{r^2}{D_r} = \left[[(Am_1(m_1-1))X^{m_1} - Bm_2(m_2-1)X^{m_2} + Cm_3(m_3-1)X^{m_3} + Dm_4(t)X^{m_4}]\right]\sin\lambda\theta \quad (10)$$

and

$$-R_r\frac{r^3}{D_r} = \left[[Am_1(m_1-1)^2 - 2\beta\lambda^2(m_1-1) - \alpha(m_1-\lambda^2)]X^{m_1} + [Bm_2(m_2-1)^2 - 2\beta\lambda^2(m_2-1) - \alpha(m_2-\lambda^2)]X^{m_2} + [Cm_3(m_3-1)^2 - 2\beta\lambda^2(m_3-1) - \alpha(m_3-\lambda^2)]X^{m_3} + [Dm_4(m_4-1)^2 - 2\beta\lambda^2(m_4-1) - \alpha(m_4-\lambda^2)]X^{m_4}\right]\sin\lambda\theta \quad (11)$$

The Finite Element Method:-
Many challenges face designers of modern engineering structures. Among them include the development of a reliable model capable of predicting the behavior of engineering designs in cost effective time scale. The Finite Element Method is a very powerful one, and it lends itself effectively to solution via computer. The method is easily

applied to any structure with complex geometry made up of one or more materials and having a mixed set of boundary conditions (Zienkiewcz, 1971).

This approach discretizes the structure into small divisions (elements) where each element is defined by a specified number of nodes. The behavior of each element (and ultimately the structure) is assumed to be a function of its nodal quantities (displacements and/or stresses), that serve as the primary unknowns in this formulation. This is one of the most general and accurate methods to use, because it does not put any limitation on the geometry, loads, or boundary conditions, and can be applied to open/closed girders and static/dynamic analysis. Additionally, the structure's response can always be improved by refining the mesh and increasing the number of nodes (or degrees of freedom) for each element. However, the rather involved modeling and analysis efforts required by this method may in some cases make it impractical for preliminary analysis (Benedetti and Tralli, 1989).

The finite method of analysis is a widely accepted numerical technique for the solution of a wide variety of problems found in engineering. The method is now by far the most effective tool available to analysts interested in computer assisted solutions of complex engineering problems. The method has the virtue of simplicity in concept, precision in development and potency in application. As a result of this, there exist at present numerous computer programs that can handle, at reasonable cost, very large finite element systems of great engineering significance. Accuracy and efficiency are the two major concerns in any finite element analysis that are forcing engineers and design analysts to seek reliable yet economical methods to determining the responses of structural components (Shim, et al, 2002; Lydzinski and Baber, 2008)

Finite Element Method is a generalization of standard structural analysis procedures, which permits the calculation of stresses in two or three dimensional structures. It approximates the governing differential equations for a given system with a set of algebraic equations relating to a finite number of variables to specific points called nodes. This method can be used for solving structural frameworks and other elastic continua utilizing discrete elements. The solution obtained in this case for joints displacements and member forces are identical to solutions obtained using other structural analysis methods (Cook, et al, 1989).

The Finite Element Method of analysis consists of a computer model of a material or design that is stressed and analyzed for specific results. The Finite Element Method originated as a method of stress analysis. Today, finite elements are also used to analyze problems of heat transfer, fluid flow, lubrication, electric and magnetic fields and many others (Monaghan, 2001). Problems that previously were utterly intractable are now solved routinely. Results are rarely exact. However, errors are reduced by processing more equations and results accurate enough for engineering purposes are obtainable at reasonable cost. In general, Finite Element Method models a structure as an assemblage of small parts (elements). Each element is of simple geometry and therefore is much easier to analyze than the actual structure. In essence, we approximate a complicated solution by a model that consists of piece wise continuous simple solutions. Elements are called 'finite' to distinguish them from differential elements used in calculus (Cook, et al, 1989).

Bride load Model:-

The loads considered in this research are the dead and live load component. The load model is based on AASHTO LRFD (2004) specifications. The dead load components used include factory made member weight (girders), deck slab and wearing coarse. Live load parameters are derived from AASHTO (2004) which is designated as HL-93. The models used considered various positions for both single and multiple lane loads to obtain maximum moment on the deck for transverse truck locations. Figure 1 shows the truck location, which is 0.15m close to the center line.

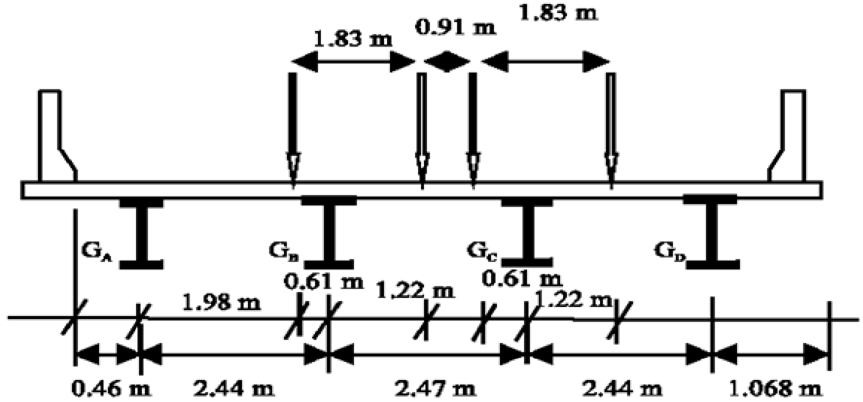

Fig. 1: Typical transverse section of bridge showing HL-93 loading location (AASHTO, 2004)

ABAQUS Software:-

The ABAQUS is a suite of powerful engineering simulation programs, based on the finite element method, that can solve problems ranging from relatively simple linear analyses to the most challenging nonlinear simulations. ABAQUS contains an extensive library of elements that can model virtually any geometry. It has an equally extensive list of material models that can simulate the behavior of most typical engineering materials including metals, rubber, polymers, composites, reinforced concrete, crushable and resilient foams, and geotechnical materials such as soils and rock (Simulia, 2010).

ABAQUS offers a wide range of capabilities for simulation of linear and nonlinear applications.Problems with multiple components are modeled by associating the geometry defining each component with the appropriate material models and specifying component interactions. The ABAQUS Version 6.10 is employed for the analysis in this work. It was used to study the variation of load with the nodal displacement. With this result it is possible to determinehow durable the proposed horizontally curved Aluminium alloy bridge deck is under applied stress representing the wheel stresses, dead weight stresses and the centrifugal stresses.

Results and discussion:-

The deck was analyzed using Finite Element software ABAQUS. The figure below illustrates the case study considered - a horizontally curved aluminium alloy deck - Alumadeck™ –Radius = $100m$, Subtended angle = 34.4°, Modulus of elasticity of the 6063T6 Aluminium, E_A = $68.9GPa$

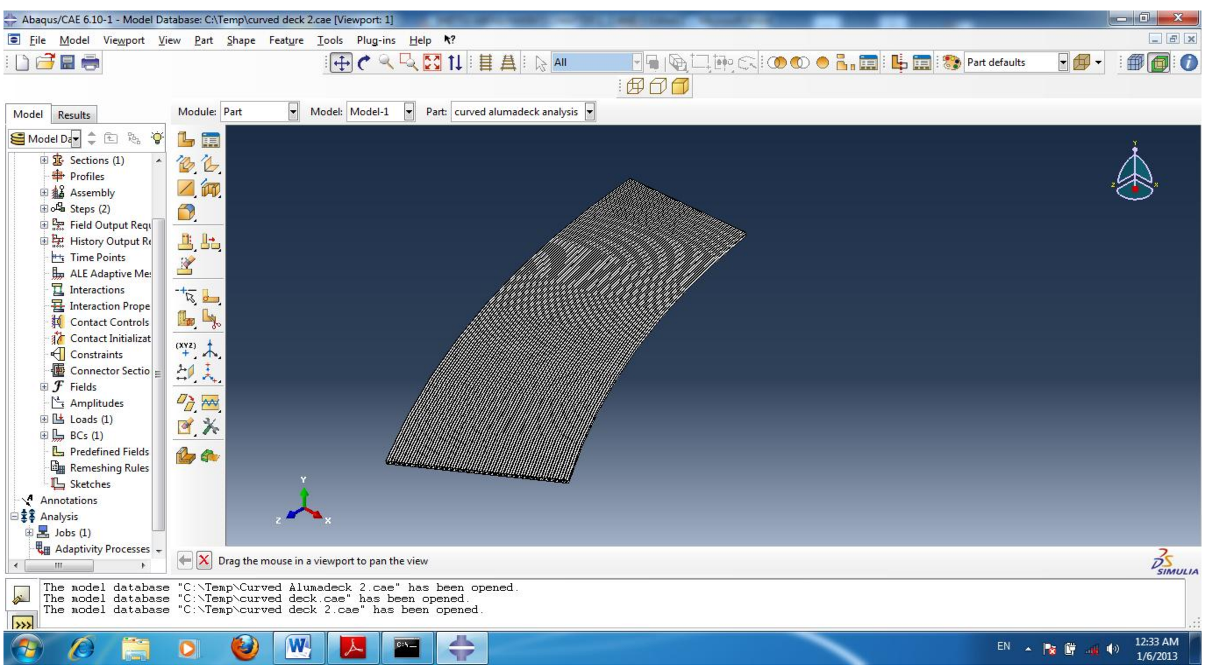

Figure 1: The horizontally curved bridge deck as drawn in ABAQUS.

The Figure 2 below shows the Alumadeck section used (Seethe vertical and inclined stiffeners, and top and bottom chords). The solid element feature of ABAQUS was used.

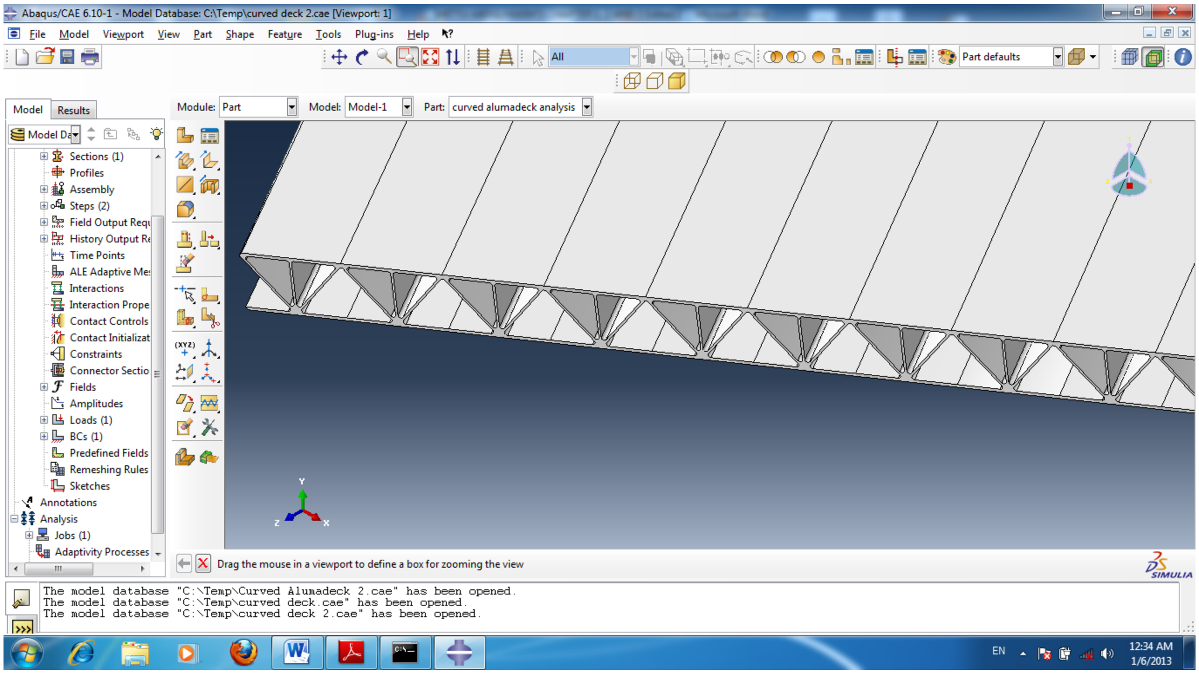

Figure 2: The ABAQUS showing the vertical and inclined stiffners of the horizontally curved Aluminium alloy deckSee Table A-1 to Table A-6 in Appendix A for the results of Maximum Displacements at various thicknesses of stiffener.

Conclusion:-

The result of the finite element analysis shows that the maximum displacement of the Alumadeck increases linearly with increase in the applied centrifugal stresses. The displacements are acceptable generally and this is an indication of the durability of the Alumadeck. It is recommended that the thickness of stiffeners should be a minimum of $7mm$ to have a safer structure since some of the maximum displacements for the $5mm$ were not satisfactory.

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APPENDIX A:-

Table A-1: Maximum Displacements at a Thickness of stiffener = $50mm$

	Maximum Displacement, Umax (mm) at various applied stresses (KN per sq.m) at a Thickness of stiffner = 50mm							
Applied Centrifugal Stresses (KN per sq.m)	50	100	150	200	250	300	350	400
10	4.78E-04	9.52E-04	1.43E-03	1.90E-03	2.37E-03	2.85E-03	3.32E-03	3.80E-03
20	4.81E-04	9.55E-04	1.43E-03	1.90E-03	2.38E-03	2.85E-03	3.33E-03	3.80E-03
40	4.88E-04	9.62E-04	1.44E-03	1.91E-03	2.39E-03	2.86E-03	3.33E-03	3.81E-03
60	4.95E-04	9.69E-04	1.44E-03	1.92E-03	2.39E-03	2.87E-03	3.34E-03	3.81E-03
80	5.02E-04	9.77E-04	1.45E-03	1.93E-03	2.40E-03	2.87E-03	3.35E-03	3.82E-03
100	5.10E-04	9.84E-04	1.46E-03	1.93E-03	2.41E-03	2.88E-03	3.35E-03	3.83E-03
120	5.17E-04	9.91E-04	1.47E-03	1.94E-03	2.41E-03	2.89E-03	3.36E-03	3.84E-03
140	5.24E-04	9.98E-04	1.47E-03	1.95E-03	2.42E-03	2.89E-03	3.37E-03	3.84E-03
160	5.31E-04	1.01E-03	1.48E-03	1.95E-03	2.43E-03	2.90E-03	3.38E-03	3.85E-03
180	5.38E-04	1.01E-03	1.49E-03	1.96E-03	2.43E-03	2.91E-03	3.38E-03	3.86E-03
200	5.45E-04	1.02E-03	1.49E-03	1.97E-03	2.44E-03	2.92E-03	3.39E-03	3.86E-03
220	5.52E-04	1.03E-03	1.50E-03	1.97E-03	2.45E-03	2.92E-03	3.40E-03	3.87E-03
240	5.59E-04	1.03E-03	1.51E-03	1.98E-03	2.46E-03	2.93E-03	3.40E-03	3.88E-03

Table A-2: Maximum Displacements at a Thickness of stiffener = $70mm$

	Maximum Displacement, Umax (mm) at various applied stresses (KN per sq.m) at a Stiffner Thickness = 70mm							
Applied Centrifugal Stresses (KN per sq.m)	50	100	150	200	250	300	350	400
10	4.09E-04	8.14E-04	1.22E-03	1.63E-03	2.03E-03	2.44E-03	2.84E-03	3.25E-03
20	4.12E-04	8.17E-04	1.22E-03	1.63E-03	2.03E-03	2.44E-03	2.85E-03	3.25E-03
40	4.18E-04	8.23E-04	1.23E-03	1.63E-03	2.04E-03	2.45E-03	2.85E-03	3.26E-03
60	4.24E-04	8.29E-04	1.24E-03	1.64E-03	2.05E-03	2.45E-03	2.86E-03	3.26E-03
80	4.30E-04	8.35E-04	1.24E-03	1.65E-03	2.05E-03	2.46E-03	2.86E-03	3.27E-03
100	4.36E-04	8.41E-04	1.25E-03	1.65E-03	2.06E-03	2.46E-03	2.87E-03	3.27E-03
120	4.42E-04	8.47E-04	1.25E-03	1.66E-03	2.06E-03	2.47E-03	2.88E-03	3.28E-03
140	4.48E-04	8.53E-04	1.26E-03	1.66E-03	2.07E-03	2.48E-03	2.88E-03	3.29E-03
160	4.54E-04	8.59E-04	1.27E-03	1.67E-03	2.08E-03	2.48E-03	2.89E-03	3.29E-03
180	4.60E-04	8.65E-04	1.27E-03	1.68E-03	2.08E-03	2.49E-03	2.89E-03	3.30E-03
200	4.66E-04	8.71E-04	1.28E-03	1.68E-03	2.09E-03	2.49E-03	2.90E-03	3.31E-03
220	4.72E-04	8.78E-04	1.28E-03	1.69E-03	2.09E-03	2.50E-03	2.91E-03	3.31E-03
240	4.78E-04	8.84E-04	1.29E-03	1.70E-03	2.10E-03	2.51E-03	2.91E-03	3.32E-03

Table A-3: Maximum Displacements at a Thickness of stiffener = $90mm$.

	Maximum Displacement, Umax (mm) at various applied stresses (KN per sq.m) at a Stiffner Thickness = 90mm							
Applied Centrifugal Stresses (KN per sq.m)	50	100	150	200	250	300	350	400
10	3.77E-04	7.52E-04	1.13E-03	1.50E-03	1.88E-03	2.25E-03	2.63E-03	3.00E-03
20	3.80E-04	7.54E-04	1.13E-03	1.50E-03	1.88E-03	2.25E-03	2.63E-03	3.00E-03
40	3.85E-04	7.59E-04	1.13E-03	1.51E-03	1.88E-03	2.26E-03	2.63E-03	3.01E-03
60	3.90E-04	7.64E-04	1.14E-03	1.51E-03	1.89E-03	2.26E-03	2.64E-03	3.01E-03
80	3.94E-04	7.69E-04	1.14E-03	1.52E-03	1.89E-03	2.27E-03	2.64E-03	3.02E-03
100	3.99E-04	7.74E-04	1.15E-03	1.52E-03	1.90E-03	2.27E-03	2.65E-03	3.02E-03
120	4.04E-04	7.79E-04	1.15E-03	1.53E-03	1.90E-03	2.28E-03	2.65E-03	3.03E-03
140	4.09E-04	7.84E-04	1.16E-03	1.53E-03	1.91E-03	2.28E-03	2.66E-03	3.03E-03
160	4.14E-04	7.89E-04	1.16E-03	1.54E-03	1.91E-03	2.29E-03	2.66E-03	3.04E-03
180	4.19E-04	7.94E-04	1.17E-03	1.54E-03	1.92E-03	2.29E-03	2.67E-03	3.04E-03
200	4.24E-04	7.99E-04	1.17E-03	1.55E-03	1.92E-03	2.30E-03	2.67E-03	3.05E-03
220	4.29E-04	8.04E-04	1.18E-03	1.55E-03	1.93E-03	2.30E-03	2.68E-03	3.05E-03
240	4.34E-04	8.08E-04	1.18E-03	1.56E-03	1.93E-03	2.31E-03	2.68E-03	3.06E-03

Table A-4: Von Mises stresses at a Thickness of stiffener = $50mm$.

	Von Misses stress (kN per sq. m) at various applied stresses (KN per sq.m) at a Thickness of stiffner = 50mm							
Applied Centrifugal Stresses (KN per sq.m)	50	100	150	200	250	300	350	400
10	1.18E+04	2.36E+04	3.53E+04	4.71E+04	5.89E+04	7.06E+04	8.24E+04	9.42E+04
20	1.23E+04	2.54E+04	3.54E+04	4.71E+04	5.89E+04	7.07E+04	8.24E+04	9.42E+04
40	1.27E+04	2.47E+04	3.54E+04	4.72E+04	5.89E+04	7.07E+04	8.25E+04	9.42E+04
60	1.30E+04	2.50E+04	3.70E+04	4.72E+04	5.90E+04	7.08E+04	8.25E+04	9.43E+04
80	1.34E+04	2.54E+04	3.74E+04	4.93E+04	5.81E+04	7.08E+04	8.26E+04	9.44E+04
100	1.38E+04	2.57E+04	3.77E+04	4.97E+04	6.17E+04	7.09E+04	8.26E+04	9.44E+04
120	1.63E+04	2.61E+04	3.80E+04	5.00E+04	6.20E+04	7.40E+04	8.27E+04	9.45E+04
140	1.64E+04	2.64E+04	3.84E+04	5.04E+04	6.24E+04	7.44E+04	8.64E+04	9.45E+04
160	1.64E+04	2.68E+04	3.87E+04	5.07E+04	6.27E+04	7.47E+04	8.67E+04	9.87E+04
180	1.70E+04	2.71E+04	3.91E+04	5.11E+04	6.31E+04	7.50E+04	8.70E+04	9.90E+04
200	1.82E+04	2.75E+04	3.94E+04	5.14E+04	6.34E+04	7.54E+04	8.74E+04	9.94E+04
220	1.94E+04	3.26E+04	3.98E+04	5.18E+04	6.37E+04	7.57E+04	8.77E+04	9.97E+04
240	2.06E+04	3.26E+04	4.02E+04	5.21E+04	6.41E+04	7.61E+04	8.81E+04	1.00E+05

Table A-5: Von Mises stresses at a Thickness of stiffener = 70mm.

	Von Misses stress (kN per sq. m) at various applied stresses (KN per sq.m) at a Thickness of stiffner = 70mm							
Applied Centrifugal Stresses (KN per sq.m)	50	100	150	200	250	300	350	400
10	1.05E+04	2.08E+04	3.11E+04	4.14E+04	5.18E+04	6.21E+04	7.24E+04	8.27E+04
20	1.06E+04	2.09E+04	3.13E+04	4.16E+04	5.19E+04	6.22E+04	7.25E+04	8.29E+04
40	1.09E+04	2.12E+04	3.15E+04	4.19E+04	5.22E+04	6.25E+04	7.28E+04	8.31E+04
60	1.12E+04	2.15E+04	3.18E+04	4.22E+04	5.25E+04	6.28E+04	7.31E+04	8.34E+04
80	1.15E+04	2.18E+04	3.21E+04	4.24E+04	5.28E+04	6.31E+04	7.34E+04	8.37E+04
100	1.18E+04	2.21E+04	3.24E+04	4.27E+04	5.31E+04	6.34E+04	7.37E+04	8.40E+04
120	1.22E+04	2.24E+04	3.27E+04	4.30E+04	5.33E+04	6.37E+04	7.40E+04	8.43E+04
140	1.25E+04	2.27E+04	3.30E+04	4.33E+04	5.36E+04	6.40E+04	7.43E+04	8.46E+04
160	1.28E+04	2.30E+04	3.33E+04	4.36E+04	5.39E+04	6.42E+04	7.46E+04	8.49E+04
180	1.35E+04	2.34E+04	3.36E+04	4.39E+04	5.42E+04	6.45E+04	7.49E+04	8.52E+04
200	1.44E+04	2.37E+04	3.39E+04	4.42E+04	5.45E+04	6.48E+04	7.52E+04	8.55E+04
220	1.53E+04	2.40E+04	3.42E+04	4.45E+04	5.48E+04	6.51E+04	7.54E+04	8.58E+04
240	1.61E+04	2.43E+04	3.46E+04	4.48E+04	5.51E+04	6.54E+04	7.57E+04	8.61E+04

Table A-6: Von Mises stresses at a Thickness of stiffener = 90mm

	Von Misses stress (kN per sq. m) at various applied stresses (KN per sq.m) at a Thickness of stiffner = 90mm							
Applied Centrifugal Stresses (KN per sq.m)	50	100	150	200	250	300	350	400
10	8.80E+03	1.76E+04	2.64E+04	3.52E+04	4.40E+04	5.28E+04	6.16E+04	7.04E+04
20	9.79E+03	1.76E+04	2.64E+04	3.52E+04	4.40E+04	5.28E+04	6.16E+04	7.04E+04
40	1.00E+04	1.96E+04	2.64E+04	3.52E+04	4.40E+04	5.28E+04	6.16E+04	7.04E+04
60	1.03E+04	1.98E+04	2.94E+04	3.52E+04	4.40E+04	5.28E+04	6.16E+04	7.04E+04
80	1.05E+04	2.01E+04	2.96E+04	3.92E+04	4.41E+04	5.28E+04	6.16E+04	7.04E+04
100	1.08E+04	2.03E+04	2.99E+04	3.94E+04	4.90E+04	5.29E+04	6.16E+04	7.04E+04
120	1.10E+04	2.06E+04	3.01E+04	3.96E+04	4.92E+04	5.88E+04	6.18E+04	7.04E+04
140	1.25E+04	2.08E+04	3.03E+04	3.99E+04	4.94E+04	5.90E+04	6.86E+04	7.07E+04
160	1.29E+04	2.11E+04	3.06E+04	4.01E+04	4.97E+04	5.92E+04	6.88E+04	7.83E+04
180	1.38E+04	2.13E+04	3.08E+04	4.04E+04	4.99E+04	5.95E+04	6.90E+04	7.86E+04
200	1.48E+04	2.16E+04	3.11E+04	4.06E+04	5.02E+04	5.97E+04	6.93E+04	7.88E+04
220	1.57E+04	2.18E+04	3.13E+04	4.09E+04	5.04E+04	5.99E+04	6.95E+04	7.91E+04
240	1.66E+04	2.21E+04	3.16E+04	4.11E+04	5.06E+04	6.02E+04	6.97E+04	7.93E+04

APPENDIX B

```
1
Abaqus 6.10-1                    Date 23-Oct-2013   Time 17:12:55
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         *            * N O T I C E *                              *
         *            *****************                            *
         *                                                         *
         *                                                         *
         *              Abaqus 6.10-1                              *
         *                                                         *
         *       BUILD ID: 2010_04_29-14.17.36 102575              *
         *                                                         *
         *                                                         *
         *  Please make sure you are using release 6.10manuals     *
         *  plus the notes accompanying this release.              *
         *                                                         *
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   PROCESSING PART, INSTANCE, AND ASSEMBLY INFORMATION
```

```
 ******************************************************
   END PROCESSING PART, INSTANCE, AND ASSEMBLY INFORMATION
 **********************************************************
   OPTIONS BEING PROCESSED
 ***************************

*Heading
*Node
*Element, type=C3D6
*Nset, nset="ASSEMBLY_CURVED DECK 1-1__PICKEDSET2"
*Elset, elset="ASSEMBLY_CURVED DECK 1-1__PICKEDSET2"
*Nset, nset=ASSEMBLY__PICKEDSET6
*Elset, elset=ASSEMBLY__PICKEDSET6
*Elset, elset=ASSEMBLY___PICKEDSURF4_S3
*Elset, elset=ASSEMBLY___PICKEDSURF4_S4
*Elset, elset=ASSEMBLY___PICKEDSURF4_S5
*Elset, elset=ASSEMBLY___PICKEDSURF5_S5
*surface, type=ELEMENT, name=ASSEMBLY__PICKEDSURF4
*surface, type=ELEMENT, name=ASSEMBLY__PICKEDSURF5
*surface, type=ELEMENT, name=ASSEMBLY__PICKEDSURF4
*surface, type=ELEMENT, name=ASSEMBLY__PICKEDSURF5
*material, name="CURVED ALUMADECK"
*density
*elastic
*plastic
*solidsection, elset="ASSEMBLY_CURVED DECK 1-1__PICKEDSET2", material="CURVED ALUMADECK"
*boundary
*solidsection, elset="ASSEMBLY_CURVED DECK 1-1__PICKEDSET2", material="CURVED ALUMADECK"
*surface, type=ELEMENT, name=ASSEMBLY__PICKEDSURF4
*surface, type=ELEMENT, name=ASSEMBLY__PICKEDSURF5
*output, field, variable=PRESELECT
*output, history, variable=PRESELECT
*output, field, variable=PRESELECT
*output, history, variable=PRESELECT
*output, field, variable=PRESELECT
*output, history, variable=PRESELECT
*Step, name="apply pressure"
*output, field, variable=PRESELECT
*output, history, variable=PRESELECT
*Step, name="apply pressure"
*Step, name="apply pressure"
*static
*boundary
*dsload
*dsload
*output, field, variable=PRESELECT
*output, history, variable=PRESELECT
*endstep
*Step, name="apply pressure"
*static
*boundary

***WARNING: DEGREE OF FREEDOM 4 IS NOT ACTIVE IN THIS MODEL AND CAN NOT BE
        RESTRAINED

***WARNING: DEGREE OF FREEDOM 5 IS NOT ACTIVE IN THIS MODEL AND CAN NOT BE
```

```
        RESTRAINED

***WARNING: DEGREE OF FREEDOM 6 IS NOT ACTIVE IN THIS MODEL AND CAN NOT BE
        RESTRAINED
 *output, field, variable=PRESELECT
 *output, history, variable=PRESELECT
 *endstep

   - (RAMP) OR (STEP) - INDICATE USE OF DEFAULT AMPLITUDES ASSOCIATED WITH THE STEP

   - (RAMP) OR (STEP) - INDICATE USE OF DEFAULT AMPLITUDES ASSOCIATED WITH THE STEP



                 P R O B L E M   S I Z E


      NUMBER OF ELEMENTS IS                      17172
      NUMBER OF NODES IS                         14326
      NUMBER OF NODES DEFINED BY THE USER        14326
      TOTAL NUMBER OF VARIABLES IN THE MODEL     42978
      (DEGREES OF FREEDOM PLUS MAX NO. OF ANY LAGRANGE MULTIPLIER
       VARIABLES. INCLUDE *PRINT,SOLVE=YES TO GET THE ACTUAL NUMBER.)

                  END OF USER INPUT PROCESSING

   JOB TIME SUMMARY
     USER TIME (SEC)      =   1.3000
     SYSTEM TIME (SEC)    =  0.20000
     TOTAL CPU TIME (SEC) =   1.5000
     WALLCLOCK TIME (SEC) =        2
1

Abaqus 6.10-1                      Date 23-Oct-2013   Time 17:12:58
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                                              STEP    1  INCREMENT    1
                                            TIME COMPLETED IN THIS STEP   0.00


                S T E P      1     S T A T I C   A N A L Y S I S


   AUTOMATIC TIME CONTROL WITH -
      A SUGGESTED INITIAL TIME INCREMENT OF           1.00
      AND A TOTAL TIME PERIOD OF                      1.00
      THE MINIMUM TIME INCREMENT ALLOWED IS           1.000E-05
      THE MAXIMUM TIME INCREMENT ALLOWED IS           1.00

   LINEAR EQUATION SOLVER TYPE        DIRECT SPARSE

              M E M O R Y   E S T I M A T E

 PROCESS     FLOATING PT      MINIMUM MEMORY      MEMORY TO
             OPERATIONS         REQUIRED          MINIMIZE I/O
            PER ITERATION       (MBYTES)           (MBYTES)
```

1	3.14E+009	42	160

NOTE:

(1) SINCE ABAQUS DOES NOT PRE-ALLOCATE MEMORY AND ONLY ALLOCATES MEMORY AS NEEDED DURING THE ANALYSIS,
THE MEMORY REQUIREMENT PRINTED HERE CAN ONLY BE VIEWED AS A GENERAL GUIDELINE BASED ON THE BEST
KNOWLEDGE AVAILABLE AT THE BEGINNING OF A STEP BEFORE THE SOLUTION PROCESS HAS BEGUN.

(2) THE ESTIMATE IS NORMALLY UPDATED AT THE BEGINNING OF EVERY STEP. IT IS THE MAXIMUM VALUE OF THE
ESTIMATE FROM THE CURRENT STEP TO THE LAST STEP OF THE ANALYSIS, WITH UNSYMMETRIC SOLUTION TAKEN
INTO ACCOUNT IF APPLICABLE.

(3) SINCE THE ESTIMATE IS BASED ON THE ACTIVE DEGREES OF FREEDOM IN THE FIRST ITERATION OF THE
CURRENT STEP, THE MEMORY ESTIMATE MIGHT BE SIGNIFICANTLY DIFFERENT THAN ACTUAL USAGE FOR
PROBLEMS WITH SUBSTANTIAL CHANGES IN ACTIVE DEGREES OF FREEDOM BETWEEN STEPS (OR EVEN WITHIN
THE SAME STEP). EXAMPLES ARE: PROBLEMS WITH SIGNIFICANT CONTACT CHANGES, PROBLEMS WITH MODEL
CHANGE, PROBLEMS WITH BOTH STATIC STEP AND STEADY STATE DYNAMIC PROCEDURES WHERE ACOUSTIC
ELEMENTS WILL ONLY BE ACTIVATED IN THE STEADY STATE DYNAMIC STEPS.

(4) FOR MULTI-PROCESS EXECUTION, THE ESTIMATED VALUE OF FLOATING POINT OPERATIONS FOR EACH PROCESS
IS BASED ON AN INITIAL SCHEDULING OF OPERATIONS AND MIGHT NOT REFLECT THE ACTUAL FLOATING
POINT OPERATIONS COMPLETED ON EACH PROCESS. OPERATIONS ARE DYNAMICALY BALANCED DURING EXECUTION,
SO THE ACTUAL BALANCE OF OPERATIONS BETWEEN PROCESSES IS EXPECTED TO BE BETTER THAN THE ESTIMATE
PRINTED HERE.

(5) THE UPPER LIMIT OF MEMORY THAT CAN BE ALLOCATED BY ABAQUS WILL IN GENERAL DEPEND ON THE VALUE OF
THE "MEMORY" PARAMETER AND THE AMOUNT OF PHYSICAL MEMORY AVAILABLE ON THE MACHINE. PLEASE SEE
THE "ABAQUS ANALYSIS USER'S MANUAL" FOR MORE DETAILS. THE ACTUAL USAGE OF MEMORY AND OF DISK
SPACE FOR SCRATCH DATA WILL DEPEND ON THIS UPPER LIMIT AS WELL AS THE MEMORY REQUIRED TO MINIMIZE
I/O. IF THE MEMORY UPPER LIMIT IS GREATER THAN THE MEMORY REQUIRED TO MINIMIZE I/O, THEN THE ACTUAL
MEMORY USAGE WILL BE CLOSE TO THE ESTIMATED "MEMORY TO MINIMIZE I/O" VALUE, AND THE SCRATCH DISK
USAGE WILL BE CLOSE-TO-ZERO; OTHERWISE, THE ACTUAL MEMORY USED WILL BE CLOSE TO THE PREVIOUSLY
MENTIONED MEMORY LIMIT, AND THE SCRATCH DISK USAGE WILL BE ROUGHLY PROPORTIONAL TO THE DIFFERENCE
BETWEEN THE ESTIMATED "MEMORY TO MINIMIZE I/O" AND THE MEMORY UPPER LIMIT. HOWEVER ACCURATE
ESTIMATE OF THE SCRATCH DISK SPACE IS NOT POSSIBLE.

(6) USING "*RESTART, WRITE" CAN GENERATE A LARGE AMOUNT OF DATA WRITTEN IN THE WORK DIRECTORY.

```
THE ANALYSIS HAS BEEN COMPLETED



                    ANALYSIS COMPLETE
                    WITH     3 WARNING MESSAGES ON THE DAT FILE
                    AND      1 WARNING MESSAGES ON THE MSG FILE


JOB TIME SUMMARY
  USER TIME (SEC)      =   3.9000
  SYSTEM TIME (SEC)    =  0.10000
  TOTAL CPU TIME (SEC) =   4.0000
  WALLCLOCK TIME (SEC) =          6
```