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Ting-Yu Lo

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TENSION IN THE TIE-DOWN CHAINS OF A SHIPPING CONTAINER FOR HAZARDOUS MATERIAL

Ting-Yu Lo
Lawrence Livermore National Laboratory
Livermore, California

ABSTRACT

Chains are frequently used to tie the shipping containers of hazardous material to a truck bed. The tie-down system is nonlinear when the container is subjected to a triaxial force during transit. It is nonlinear because chains cannot carry compressive force, and the base of the container may partially lift off from the truck bed. A method was developed to calculate the amount of tension in the chains. This methodology includes three assumptions: (1) No friction exists between the container and the truck bed; (2) The container and the truck bed are rigid; and (3) All chains are properly tightened (i.e., no slacks) during preparation for shipment. The methodology employs an iterative process of a linear tie-down system. This linear system is derived from the nonlinear system with two additional assumptions: (a) All chains can carry compression as well as tension; and (b) There is a point contact between the container and the truck bed. This linear system has a closed-form solution. After the first solution of the linear system is obtained, the unreasonable, or physically impossible, rotational degree of freedom of the container and the chains with compressive force are eliminated in the follow-up iterative calculations using the same linear system. Unreasonable rotation is detected when the results indicate a rotation of the container into the truck bed. Zero rotational value is assigned to this degree of freedom in the follow-up iterations. For chains under compression, the chain length is replaced with a fictitiously large value because a long chain carries essentially no load. This process usually needs only two or three iterations and can easily be carried out in a spread sheet using such programs as Microsoft Excel or LOTUS 123.

1.0 INTRODUCTION

Chains are frequently used to tie a container of hazardous material to the truck bed of a transporter. Besides the chains, a tie-down system may include other components such as the brackets or

shackles of a container, tensioners, tie-down adapters (or floor lugs), and tie-down tracks on the truck bed. For the containers designed in accordance with Title 10 of Code of Federal Regulations, Part 71 (10 CFR 71), it is required that tie-down devices which are structural parts of a package, must be capable of withstanding, without generating stress in any material of the package in excess of its yield strength, a static force applied to the center of gravity (cg) of the container and its contents. This static force should have a vertical component of two times the weight of the container and its contents, a horizontal component along the direction in which the vehicle travels of 10 times the weight, and a horizontal transverse component of five times the weight. The tie-down system needs to be designed to carry these loads.

2.0 OBJECTIVE

The objective of this study was to develop a methodology to calculate the tension force in the chains of a given tie-down system. By using trial-and-error and this methodology, it is then possible to obtain an appropriate layout (the number of chains and the length and orientation of each chain) for a tie-down system.

3.0 METHOD OF ANALYSIS

A tie-down system involving chains is nonlinear when the container is subjected to a triaxial force during transit. It is nonlinear because chains cannot carry compressive force, and the base of the container may lift off partially from the truck bed. A methodology was developed to calculate the tension force in the chains of a given tie-down system. This methodology includes the following assumptions:

- (1) No friction exists between the container and the truck bed;

- (2) Except the chains, all components including the container and the truck bed are rigid; and
- (3) All chains are properly tightened during preparation for shipment. Slack in chains is not considered in this methodology. The small preload in chains due to tightening is negligible compared to the chain force produced by the static force discussed in Section 1.0.

The methodology employs an iterative process and a linearized tie-down system. This linear system is derived from the nonlinear system with two additional assumptions: (a) All chains can carry compression as well as tension; and (b) The contact condition between the truck bed and the support system of the container is known. This given contact condition can be one of the following three: (1) a point contact; (2) a line or a two-point contact on one side of the support, and (3) a line or a two-point contact along the front edge of the support. This linear system has a closed-form solution. The mathematical formulation of this linear system is presented in Section 3.1. After the first iteration of the linear system, unreasonable or physically impossible rotational degree of freedom of the container is eliminated in the follow-up iterative calculations. Unreasonable rotation is detected when the results indicate a rotation of the container into the truck bed. This rotational degree of freedom is then constrained in the follow-up iterations. For chains under compression, the chain length is replaced with a fictitiously large value because long chain carries essentially no load. This iterative process can easily be carried out in a spread sheet using such programs as Microsoft Excel or LOTUS 123. Detailed discussion of this iterative process is presented in Section 3.2.

3.1 A Linear Tie-Down System

Figure 1 shows two kinds of coordinate systems used in this methodology for a container and its tie-down system. The global coordinate system (X , Y , and Z) is applicable to the container. The origin of this coordinate system can be located anywhere at the discretion of the analyst. In Fig. 1, the origin is located at Point O, which is at the left front corner of the support. The local coordinate system is for the chains. Each chain has its own local coordinate system. The origin of each of these local coordinate systems is located at the anchor point of the chain on the truck bed. These local coordinate systems are parallel to the global coordinate system. A typical local coordinate system (x , y , and z) for the chain connected to Point B (Chain 5) is also shown in Fig. 1. The total number of chains and the length and orientation of these chains are assumed to be known for the given tie-down system.

3.1.1 A Typical Chain

For a typical chain (for example, Chain 5 connected to Point B) we have the following:

$$\text{Chain length, } S = \sqrt{x^2 + y^2 + z^2} - c.$$

Elongation of the chain,

$$d_s = (xd_x + yd_y + zd_z) / (s + c).$$

$$\text{Spring constant, } k = na / s.$$

Force in the chain,

$$F = kd_s = na(xd_x + yd_y + zd_z) / [s(s + c)]$$

In the above equations,

c = the length of the rigid tensioner for the chain,

n = actual number of chains used for the chain under consideration,

a = a chain property depending on the size and material properties of the chain,

d_i = displacement in direction "i" of Point B ("i" can be x , y , or z) relative to the truck bed, and

(x, y, z) = coordinates of Point B in the local coordinate system.

Throughout this calculation, it is not necessary to know the exact value of "a" because it is canceled out in the calculation of chain forces if the same type (size and material) of chains is used throughout the tie-down system. If the displacement of the container relative to the truck bed or the elongation of a chain is needed, the actual value of "a" is then required.

For a given displacement vector ($d_x, d_y, d_z, d_{xx}, d_{yy}, d_{zz}$) of the rigid container at Point O, the displacement vector of Point B can be expressed as functions of $d_x, d_y, d_z, d_{xx}, d_{yy}$, and d_{zz} .

$$\begin{Bmatrix} d_x \\ d_y \\ d_z \\ d_{xx} \\ d_{yy} \\ d_{zz} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & Z & -Y \\ 0 & 1 & 0 & -Z & 0 & X \\ 0 & 0 & 1 & Y & -X & 0 \end{bmatrix} \begin{Bmatrix} d_x \\ d_y \\ d_z \\ d_{xx} \\ d_{yy} \\ d_{zz} \end{Bmatrix}$$

where X , Y , and Z are the coordinates of Point B, the typical point of the container, in the global coordinate system.

The components of the chain force F in the x , y , and z (or X , Y , and Z) directions are as follows:

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix} = \begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix} = \frac{F}{s + c} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix},$$

where x , y , and z are the coordinates of Point B in the local coordinate system.

The moments about the X, Y, and Z axes due to the chain force F acting on the container at Point B are

$$\begin{Bmatrix} M_{xo} \\ M_{yo} \\ M_{zo} \end{Bmatrix} = \begin{Bmatrix} M_{xo} \\ M_{yo} \\ M_{zo} \end{Bmatrix} = \begin{bmatrix} 0 & -Z & Y \\ Z & 0 & -X \\ -Y & X & 0 \end{bmatrix} \begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix}$$

The above formulas for the chain connected to Point B are applicable to other chains of the tie-down system.

3.1.2 Equilibrium of the Container

3.1.2.1 Equations of Equilibrium

Under the external static force shown in Fig. 1, the equilibrium equations for the container considering the forces in all of the chains are as follows:

$$\sum_{i=1}^m (F_x)_i = 10W$$

$$\sum_{i=1}^m (F_y)_i = 5W$$

$$\sum_{i=1}^m (F_z)_i = 2W + R_0 + R_1 + R_2$$

$$\sum_{i=1}^m (M_x)_i = 2WY_{cg} - 5WZ_{cg} + R_2Y_2$$

$$\sum_{i=1}^m (M_y)_i = 10WZ_{cg} - 2WX_{cg} - R_1X_1$$

$$\sum_{i=1}^m (M_z)_i = 5WX_{cg} - 10WY_{cg}$$

where

- W = Total weight of the container and its contents,
- R_0 = Reaction force of truck bed at Point O,
- R_1 = Reaction force of truck bed at left rear corner of the support,
- R_2 = Reaction force of truck bed at right front corner of the support,
- m = total number of chains,
- (X_{cg}, Y_{cg}, Z_{cg}) = coordinates of the CG of the container and its contents,
- $(X_1, 0.0, 0.0)$ = coordinates of the reaction force R_1 in global coordinate system,

$(0.0, Y_2, 0.0)$ = coordinates of the reaction force R_2 in global coordinate system.

The above equilibrium equations are for a static load with 10g longitudinal, 5g lateral, and 2g vertical components. Similar equations can be obtained for other loading conditions if necessary.

3.1.2.2 Loading and Boundary Conditions

The boundary conditions for four loading cases are as follows:

Case 1 - 10g Forward Load

$$d_y = d_z = d_{xx} = d_{zz} = 0.$$

Case 2 - 5g Lateral Load

$$d_z = d_{yy} = 0.$$

Case 3 - 2g Vertical Load

$$R_0 = R_1 = R_2 = 0.$$

Case 4 - 10g Forward, 5g Lateral, and 2g Vertical Load

$$d_z = 0.$$

If the container and truck bed have more than one point of contact, one of the following two boundary conditions is also applicable.

$$d_{xx} = 0 \text{ (if } R_1=0), \text{ and}$$

$$d_{yy} = 0 \text{ (if } R_2=0).$$

3.2 Iterative Process in Solving the Equations of Equilibrium

Spread sheet programs such as LOUITS 123 or Microsoft Excel may be used to perform calculations in accordance with the equations presented in Section 3.1. In those equations, the variables are d_x , d_y , d_z , d_{xx} , d_{yy} , d_{zz} , R_0 , R_1 , and R_2 . Straightforward elimination of variable method may be used to solve these equations. For loading and boundary conditions 1, 2 and 3, the solution can be obtained easily because many variables are zero and it is very clear which of the variables, R_1 or R_2 , is zero. Chains in compression can be eliminated by assigning fictitiously long chain length because a long chain will have small stiffness and, therefore, carry little load. The iterative process used to eliminate the chains with compressive force is straightforward and can be done easily on the spread sheet.

For loading and boundary condition 4, the iterative process is more complicated because it is not clear at the outset which of the variables R_1 and R_2 will be active because the container may rotate about any of the two horizontal axes. It may also pivot at Point O. The first step in this iterative process is to assume that both R_1 and R_2 are equal to zero (that is $d_{xx} \neq 0$ and $d_{yy} \neq 0$) and

there is only one point of contact between the container and the truck bed. The results of this iteration will provide the necessary clue because either d_{xx} or d_{yy} will most likely be unrealistic due to the limitation that the container simply cannot rotate into the truck bed. In this initial iteration, the other type of iteration required to eliminate chains with compressive force can also be carried out. Once it is known which of d_{xx} and d_{yy} is equal to zero, the same process, although with slightly different boundary conditions, can be repeated to obtain the final solution.

The analysis method described above was validated by a three dimensional finite element analysis of a sample problem using NIKE3D code, which is available at the Lawrence Livermore National Laboratory. Close agreement was observed between spread sheet results using the analysis methodology described above and the finite element analysis results.

4.0 A SAMPLE ANALYSIS

The tie-down system of a sample shipping container is shown in Fig. 1. This system has 20 chains and was the result of several trial-and-error studies using the spread sheet calculations described above. It started with 24 chains. The tie-down system is symmetrical about a vertical plane through the longitudinal axis of the container. The shackles or brackets are identified with letters A through J and the chains are numbered from 1 to 12 on each side of the container. Only the chains on the right-hand-side (RHS) of the container are shown in Fig. 1. Chains 1 and 12 on both sides were eliminated during the trial-and-error studies and are also not shown in the figure. Chains 6 and 11 include two actual chains each. Please note that each of brackets A, E, F, and J include two actual brackets. One is in the front and the other is in the back of the support cradles.

The analysis results for Case 4 loading and boundary conditions are presented in Table 1. The forces and force components in the chains are shown on the left hand side (LHS) of each table; the forces and force components on the brackets or shackles are shown on the right hand side. The total truck bed reaction force is provided at the bottom of these tables. Most of the forces are presented as multiples of the total weight (W) of the container

and its contents. The container shown in Fig. 1 has a total weight of 3000 pounds. The columns under d_x , d_y , d_z , d_{xx} , d_{yy} , d_{zz} headings show the axial forces in the chains due to the effect of individual displacement component of container in the X, Y, and Z directions and rotations about X, Y, and Z axes in the global coordinate system.

Under Case 4 loading conditions, the container rotates about the Y axis, i.e., $d_{xx}=0$, which was found during the iteration described in Section 3.2. For Chains 2, 4, 7 and 9, which are connected to lower elevation brackets, the tension is due mainly to container translation (d_x) in the longitudinal direction. The tension force in chains 6 and 11 on the RHS is due to the combined effect of translation d_y and torsion d_{zz} . Chains 6 and 11 on the LHS have zero tension force due to the 5g lateral load. For chains (Chains 5 and 10) connected to higher elevation shackles of the container, their tension forces are mainly due to rotation (d_{yy}) of the container. The tension force in Chain 10 is lower than that of Chain 5 because Chain 10 is closer to the axis of rotation. Chains 5 and 10 on the RHS have larger tension force than those on the LHS due to the translational component d_y of the container. Chain 4 carries more load than Chain 2 because it is shorter and therefore stiffer. The same is true for Chains 7 and 9. Chains 3 and 8 are in front of the container and, therefore, carry no load or very small load.

5.0 SUMMARY AND CONCLUSIONS

A methodology was developed to calculate the tension force in the chains of a tie-down system of a shipping container. This methodology employs an iterative process and a linearized tie-down system. The spread sheet program LOTUS 123 was used to implement this methodology. Sensitivity studies can conveniently be carried out on this spread sheet to design the tie-down system of a shipping container. Because the effects of each of the container displacement components (d_x , d_y , d_z , d_{xx} , d_{yy} , and d_{zz}) can be calculated, the effectiveness of each chain can easily be observed or identified. This capability helps the tie-down design tremendously. This methodology was applied to a sample shipping container with satisfactory result.

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**TABLE 1 TENSION IN THE TIE-DOWN CHAINS OF A SAMPLE SHIPPING CONTAINER
UNDER A 10G LONGITUDINAL, 5G TRANSVERSE, AND 2G VERTICAL LOAD**

SUMMARY

Case HSXYZ - SST Configuration (dZ=dXX=0)

(File: HSXYZ4.WKS)

(2/14/94)

----- Axial Force -----											----- Forces on Brackets -----										
due to disp. at pivot point																					
LHS	dX	dY	dXX	dYY	dZZ	Force	Force	FX	FY	FZ	LHS	Brkets	Chains	For-X	For-Y	For-Z	Axial	Axial			
	(W)	(W)	(W)	(W)	(W)	(W)	kips	(W)	(W)	(W)				(W)	(W)	(W)	(W)	(kips)			
1	.00	.00	0.00	.00	.00	.00	.00	.00	.00	.00	1										
2	1.24	-0.26	0.00	0.18	-0.17	0.99	2.98	0.93	-0.32	0.15	2 I	Left- 10		0.02	-0.03	0.12	0.12	0.4			
3	.00	.00	0.00	.00	.00	.00	.00	.00	.00	.00	3										
4	1.56	-0.40	0.00	0.25	-0.27	1.15	3.44	1.04	-0.44	0.20	4 J/fnt	Left- 11,8		.00	.00	.00	.00	.0			
5	0.15	-0.13	0.00	0.59	-0.09	0.51	1.54	0.08	-0.13	0.49	5 J/bck	Left- 7,9		2.31	-1.09	0.50	2.60	7.8			
6	.00	.00	0.00	.00	.00	.00	.00	.00	.00	.00	6										
7	1.60	-0.42	0.00	0.12	-0.05	1.25	3.75	1.13	-0.48	0.23	7 D	Left- 5		0.08	-0.13	0.49	0.51	1.5			
8	.00	.00	0.00	.00	.00	.00	.00	.00	.00	.00	8										
9	1.83	-0.55	0.00	0.14	-0.07	1.35	4.06	1.19	-0.59	0.27	9 E/fnt	Left- 6,3		.00	.00	.00	.00	.0			
10	0.12	-0.14	0.00	0.16	-0.02	0.12	0.37	0.02	-0.03	0.12	10 E/bck	Left- 2,4		1.97	-0.76	0.35	2.14	6.4			
11	.00	.00	0.00	.00	.00	.00	.00	.00	.00	.00	11										
12	.00	.00	0.00	.00	.00	.00	.00	.00	.00	.00	12										
Sum of LHS = 5.38 16.14 4.38 -2.00 1.45											C	Right- 1		.00	.00	.00	.00	.00	.0		
												Left- 1									
----- Axial Force -----																					
due to disp. at pivot point																					
RHS	dX	dY	dXX	dYY	dZZ	Force	Force	FX	FY	FZ	RHS										
	(W)	(W)	(W)	(W)	(W)	(W)	kips	(W)	(W)	(W)											
1	.00	.00	0.00	.00	.00	.00	.00	.00	.00	.00	1										
2	1.24	0.26	0.00	0.18	-0.07	1.61	4.82	1.50	0.52	0.24	2 G	Right- 10		0.05	0.10	0.39	0.41	1.2			
3	-2.55	1.11	0.00	0.39	1.29	0.25	0.74	-0.19	0.14	0.08	3										
4	1.56	0.40	0.00	0.25	-0.03	2.18	6.53	1.97	0.84	0.38	4 F/fnt	Right-11,8		-0.45	1.42	0.65	1.62	4.9			
5	0.15	0.13	0.00	0.59	0.07	0.94	2.83	0.15	0.23	0.90	5 F/bck	Right-7,9		3.65	1.72	0.78	4.11	12.3			
6	-1.54	1.75	0.00	0.73	1.54	2.49	7.48	-1.07	2.04	0.93	6										
7	1.60	0.42	0.00	0.12	-0.26	1.88	5.65	1.70	0.74	0.34	7 B	Right- 5		0.15	0.23	0.90	0.94	2.8			
8	.00	.00	0.00	.00	.00	.00	.00	.00	.00	.00	8										
9	1.83	0.55	0.00	0.14	-0.28	2.23	6.69	1.95	0.98	0.45	9 A/fnt	Right- 6,3		-1.27	2.18	0.99	2.71	8.1			
10	0.12	0.14	0.00	0.16	.00	0.41	1.23	0.05	0.10	0.39	10 A/bck	Right-2,4		3.48	1.36	0.62	3.78	11.3			
11	-1.08	2.05	0.00	0.14	0.51	1.62	4.86	-0.45	1.42	0.65	11										
12	.00	.00	0.00	.00	.00	.00	.00	.00	.00	.00	12										
Sum of RHS =13.60 40.81 5.62 7.00 4.34											Loads										
RHS + LHS = 19.0 56.9 10.00 5.00 5.79											Ax Ay Az										
											10.0 5.0 2.0 g's										

NOTE: Chains #6 and #11 include two chains each. Axial force = half.

Truck Bed Reaction force = 3.79 W = 11.38 kips