Variation of Lift Load Distribution Due to Sling Length Tolerance

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INTRODUCTION

Sling tension calculations made for engineered lifts typically assume that all of the slings are of the exact specified lengths. Some codes, particularly in the offshore industry,[1,2] provide load or skew factors by which these tensions are multiplied to attempt to account for variations in the lengths. Another approach often used assigns a somewhat arbitrary split of the total lifted load between diagonally opposite pairs of slings in a four-point lift, e.g., 75% of the load to one pair and the remaining 25% to the other.[3] Both of these methods have the same major problem: they deal with the symptom rather than with the problem.

This paper shall present the results of a computer study that evaluates the effect of sling length tolerance on load distribution among a set of four slings. Both sling stiffness and lifted load stiffness were varied to examine the resulting changes in sling tension. More importantly, load distribution within the lifted load framing was tabulated and compared to the framing loads obtained by application of the above referenced code provisions. Recommendations are then made which suggest a means of best dealing with unknown but very probable sling length errors in design.

COMPUTER MODEL AND ANALYSES

Computer models were developed using STRUDL that represent typical equipment modules and skids found in heavy construction. Such packaging is particularly common in offshore work and is also used, albeit less frequently, in onshore construction. Loads were applied to result in lift weights of about 400 tons (363 tonnes) for the modules and 100 tons (91 tonnes) for the skids.

Two types of lifted loads were analyzed in this study: a large, fully braced, three-dimensional module (Fig. 1) and a flat unbraced skid (Fig. 2). The module was analyzed repeatedly using different modulus of elasticity values to vary the module's stiffness over a wide range. This assortment of lifted loads represents a range of torsional stiffnesses ranging from negligible (the unbraced skid) to great enough to result in a 100%/0% load split in the slings.

Sling members were proportioned to correspond to sling sizes appropriate for the subject lifts using two different safety factors. The API offshore code[1] requires a ratio of ultimate strength to calculated static load of 4.0 for lifts made at sea. OSHA[4] requires this ratio to be at least 5.0 for onshore lifts. Thus, the OSHA sling members have a cross-sectional area about 25% greater than the API slings. A modulus of elasticity of 20,000 ksi (137,900 MPa) was used for the sling members.[5,6]

Five different lift analyses were performed to evaluate the effects of the different variables:

Type 1: The loaded module or skid was analyzed with four exact length slings and no load factors;

Type 2: Sling lengths were modified by trial-and-error to produce a 75%/25% split of the load between diagonal pairs. This is a non-code requirement that the author has frequently encountered in practice;[3]

Type 3: Sling lengths were modified to the overlength/underlength limits permitted by API and DNV [0.25% of the specified length; API additionally states that the error shall not exceed 1.5 in. (38 mm)]. One pair was overlength and the other was underlength;

Type 4: Exact length slings were used and API load factors were applied to the resulting member forces. RP 2A requires that the calculated loads in all members framing into a joint at which a padeye is located be increased by a factor of 2.0 and that the calculated forces in all other members be increased by 1.35; and,

Type 5: The last analysis used modified sling lengths to induce the skew factor specified in DNV §H1.3.2.4 (static sling loads are increased by 1.25 in one pair, resulting in a 62.5%/37.5% split).

In all cases, member stress ratios were calculated using the STRUDL code check routine.

All five analyses were performed on eight lift arrangements: the module at three different values of modulus of elasticity and the skid analyzed for both sizes of slings. The Type 1 analyses provided a reference base against which all other analyses could be compared. The Type 2, 4, and 5 analyses allow evaluation of how well empirical code and specification provisions deal with the problem of sling length inaccuracies. Lastly, the Type 3 analyses investigate the actual problem by considering the potential sling length error. Because of the importance of this behavior, 11 additional

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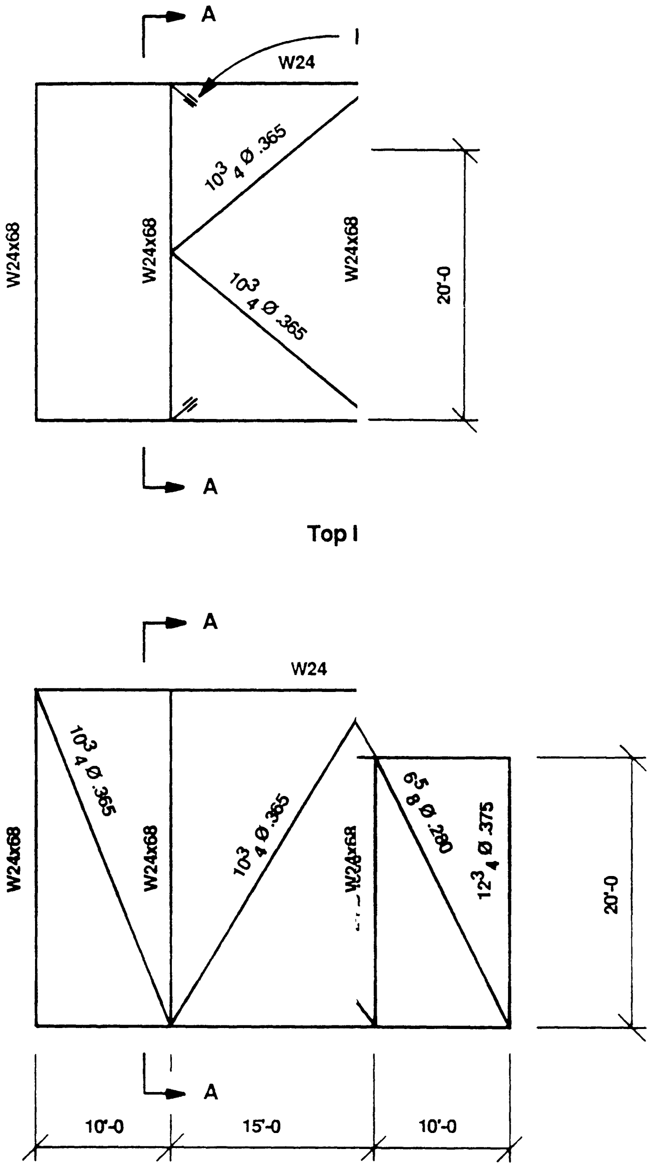

Fig. 1. Module framing plans and elevations.

Table 1. Summary of Type 3 Analysis Data			
Case	**Sling Safety Factor**	**K_{Ly}, in kips/in.**	**% Load in Heavy Pair**
1	4.0	382.92	94.3
2	5.0	382.92	100.0
3	4.0	765.84	100.0
4	5.0	765.84	100.0
5	4.0	191.46	84.9
6	5.0	191.46	89.4
7	4.0	50.04	65.8
8	5.0	50.04	66.6
9	5.0	250.22	94.4
10	4.0	300.40	91.1
11	5.0	300.40	97.8
12	5.0	320.33	98.6
13	5.0	350.37	100.0
14	4.0	450.26	96.0
15	4.0	500.44	97.3
16	4.0	550.62	98.1
17	4.0	600.79	99.6
18	4.0	0.09	50.2
19	5.0	0.09	50.2

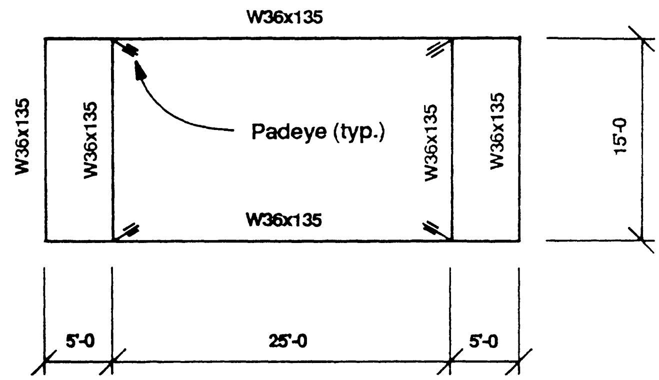

Fig. 2. Skid framing plan.

Type 3 analyses were made using a range of module torsional stiffnesses to refine the relationship between load stiffness and sling load distribution.

The stiffness of the lifted load was determined as follows. Two diagonally opposite lift points on the load were pinned as supports and a vertical load was applied to each of the other lift points (see Fig. 3). The analysis results included vertical deflections at the two loaded lift points (equal values due to symmetry). The applied load was divided by the computed deflection to give a vertical stiffness across the lifted load. This stiffness value is referred to as K_{Ly}.

The vertical stiffness components of the slings were manually calculated as $(A_sE_s/L)\sin\phi$, where ϕ is the angle of the sling with horizontal. The sling stiffness is termed K_{Sy}.

EFFECT OF API/DNV LENGTH TOLERANCE

The primary question to be answered is: What is the effect of sling length error at the limits permitted by the specifications? The Type 3 analyses yield the answer to this question. Figure 4 presents the data graphically. Two curves are shown, each corresponding to a different sling stiffness. The upper curve was developed from the module analyses with slings sized for onshore lifting (safety factor = 5.0); the lower curve represents the analysis results with slings sized for offshore work (safety factor = 4.0). Primary data for the 19 analyses used to produce Fig. 4 are assembled in Table 1.

The most obvious behavior illustrated in Fig. 4 is that an increase in the stiffness of either the load or the slings will result in an increase in the load split between pairs of slings.

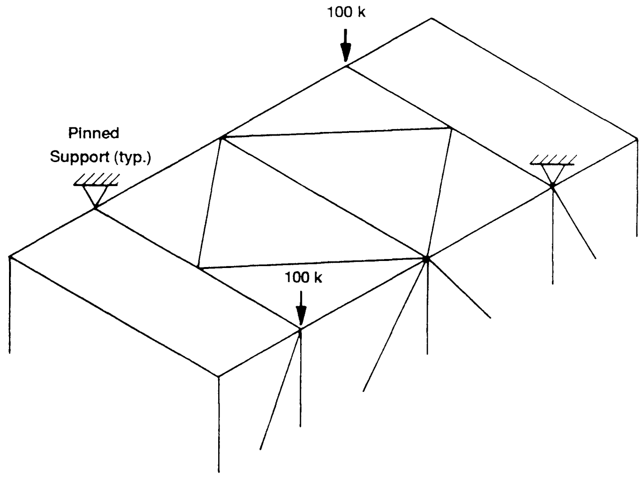

Fig. 3. Load stiffness evaluation details.

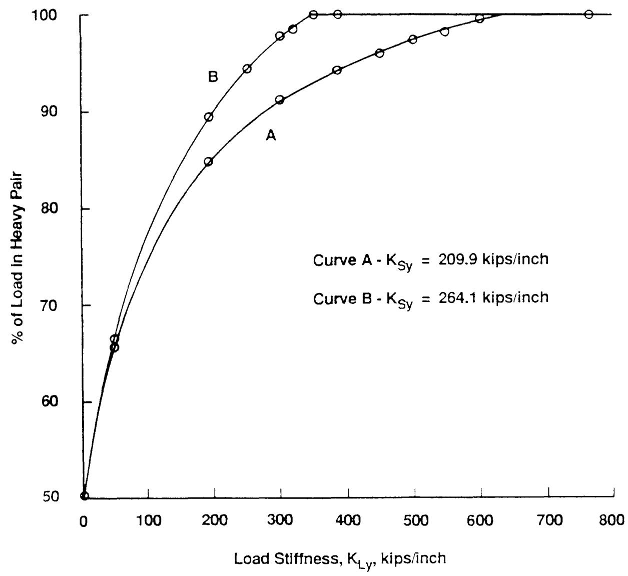

Fig. 4. Sling load split vs. load stiffness.

For relatively flexible loads, even a small increase in load stiffness results in a dramatic change in sling load distribution. At loads of greater stiffness, however, a further stiffness increase has a less pronounced effect on load distribution among the four slings.

Figure 5 presents seven short curve segments relating the sling stiffness to the load split. These curves are essentially sections cut through the two curves of Fig. 4. This figure illustrates the varying degree of sensitivity of the load split behavior to changing sling stiffness. Load distribution in a flexible load is not significantly affected by a change in sling stiffness. A rigid load is more sensitive to this effect, however.

As the sling tensions become increasingly unsymmetrical, the member forces in the lifted structure similarly change. In the module analyzed in this study, four bracing members in the top plane provide the primary resistance to horizontal racking forces due to unequal sling tensions. This bracing is detailed in Fig. 6, with member and padeye joint numbers shown. In each of the analyses in which sling length errors were specified, the sling members connected to joints 12 and 19 were the overlength slings. The slings at joints 14 and 17 were underlength.

Table 2 contains a listing of the calculated stress ratios for each of the members shown in Fig. 6. The values are taken from the module using E = 29,000 ksi (200,000 MPa) [K_{Ly} = 382.92 kips/in. (67.06 kN/mm)] and a sling safety factor of 4.0 (offshore lifting).

The two analyses that use exact length slings very seriously underestimate the forces acting in the racking bracing. Little more than the members' dead weight is creating stress in these members. When sling length errors are modeled, significant forces are induced in these members as they resist the racking caused by the horizontal components of the sling tensions.

The 62.5%/37.5% load distribution required by DNV and the 75%/25% split also considered in this study are both less than the 94.3%/5.7% split observed for this module. Reference to Fig. 4 indicates that, for this particular module, K_{Ly} must be reduced to about 100.0 kips/in. (17.5 kN/mm) to obtain a 75%/25% sling load split.

Member loads in the vertical plane framing were also generally greater when actual sling length errors were modeled, as compared to the code requirements. Because the above discussion referencing the top panel members adequately supports the point being made, the additional stress ratios will not be tabulated.

One last set of data must be introduced with respect to sling length errors. Table 3 contains typical allowable loads and strains at those loads for a range of sling sizes used in heavy rigging. For the wire rope slings, the working load strain is about 32% less than the length tolerance of 0.0025 permitted by API RP 2A. Thus, for a load of infinite stiffness, the load split will be 100%/0% if the average length error is only 0.0009, or 36% of the maximum permitted. Cable-laid slings are less stiff due to their construction, but will still produce a 100%/0% split on very rigid loads.

The allowable loads shown in Table 3 are based on manufacturers' literature[7,8] and the API safety factor of 4.0. Allowable loads for specific slings from other manufacturers

Table 2. Top Framing Stress Ratios					
Member	Exact Slings (Type 1)	75%/25% Split (Type 2)	RP 2A Toler. (Type 3)	Exact Slings, RP 2A Factors (Type 4)	DNV Skew Factor (Type 5)
10	0.33	0.21	0.16	0.62	0.27
11	0.33	0.46	0.59	0.62	0.38
14	0.33	0.46	0.59	0.62	0.38
15	0.33	0.21	0.16	0.62	0.27
45	0.50	0.84	1.10	1.06	0.68
46	0.76	0.76	0.76	1.02	0.76
47	0.50	0.37	0.29	1.06	0.40
49	0.50	0.38	0.29	1.06	0.40
50	0.50	0.84	1.10	1.06	0.68
51	0.16	0.55	0.88	0.21	0.35
52	0.16	0.69	1.14	0.21	0.41
53	0.16	0.55	0.88	0.21	0.35
54	0.16	0.69	1.13	0.21	0.40

Table 3. Working Load Strains in Typical Heavy-Lift Slings		
Sling Size, inches	Allowable Load, Tons	Strain at Allow. Load
Wire Rope Slings (E = 20,000 ksi)		
2.00	40.00	0.0018
2.50	58.75	0.0017
3.00	83.75	0.0017
3.50	110.00	0.0017
4.00	141.25	0.0016
Cable-laid Slings (E = 14,000 ksi)		
5.00	189.00	0.0028
6.00	272.50	0.0028
8.00	502.50	0.0029
10.00	742.50	0.0028
12.00	1057.50	0.0027

Allowable loads are based on the API safety factor of 4.0 for offshore lifts.

may vary due to different material grades, eye forming methods, etc.

DESIGN METHODS

Numerous variables affect the distribution of load to the slings in a four-point lift. These include sling stiffness, load stiffness, load weight and distribution, and sling length tolerance. Because of the complexity of the relationships of these variables, it is not practical to develop design curves or other aids to predict the load distribution for a certain arrangement.

Any major load similar to the module considered in this study will be analyzed by computer during the design pro-

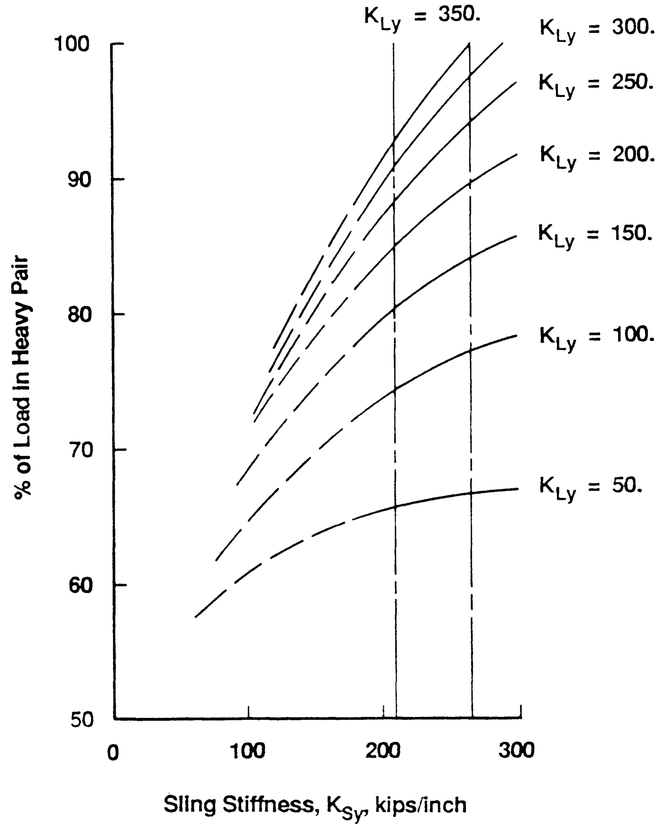

Fig. 5. Sling load split vs. sling stiffness.

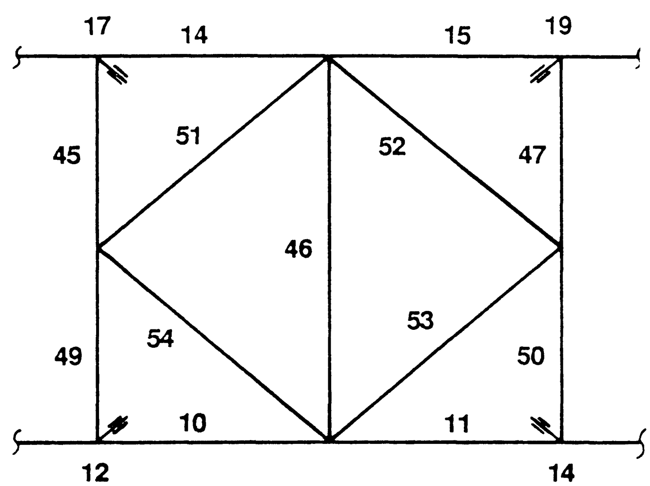

Fig. 6. Top panel framing detail.

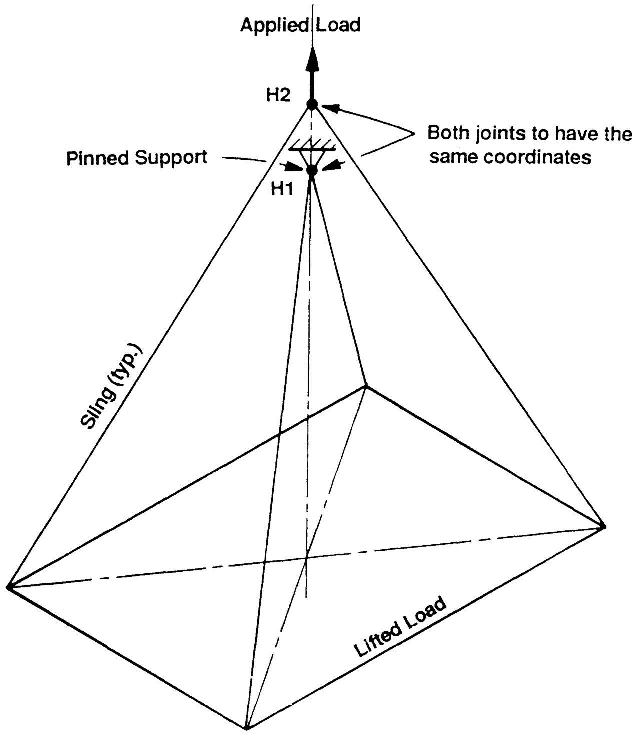

Fig. 7. Hook joint detail for induced load split

cess. The most practical approach for the lift analysis is to model the actual (or specified maximum) sling length error. Many mainframe structures programs, such as STRUDL and ANSYS, as well as some of the growing number of microcomputer programs, have the capability of accepting an initial axial strain definition. This feature can be used to specify the length error. In the absence of an initial strain capability, thermal loads can be used to shrink or elongate a sling member, as necessary. Simply select a temperature load acting along the full length of the sling member such that Temperature * Coefficient of Thermal Expansion = Required Sling Length Error (i.e., $384.6°F * 6.5 * 10^{-6} = 0.0025$).

Given a basic program with no capability for altering the member length, an approximation must be used. Consider the sling/support detail shown in Fig. 7. Joints H1 and H2, both with the same coordinates, represent the hook. H1 is fixed as a pinned support; a vertical load is applied to H2. The load at H2 is that part of the total lifted load assumed to be carried by one pair of slings. The remaining load will be taken by the support reaction at H1.

Here, the engineer must estimate the percentage of the load carried by one pair of slings. Based on the above discussion and analysis results, one should assume a load split on the order of 95%/5% as a minimum for any type of load other than a torsionally unbraced skid. Unless more information specific to the lift under consideration is available, it is very difficult to justify a smaller split. It must be noted here that the sling load distribution calculation method presented in Ref. 3 was found to be very unconservative when compared to the results in this study. The predicted transfer of load from one pair of slings to the other was typically only 30% of the actual load shift determined in the analyses.

To account for asymmetry in both the structure and the loading, the lift analysis must be run twice, once with H1 as the heavy side and once with it as the light side. This two-run requirement applies regardless of which method is used to account for the sling length tolerance.

SUMMARY AND CONCLUSIONS

Engineers have intuitively recognized that length tolerances in the sling manufacturing process may result in variations in the distribution of the lifted load among the slings. Certain codes, particularly in the offshore industry, have attempted to account for this effect by providing factors by which loads for exact length slings are multiplied. This paper has presented the results of a study that examined the effects of sling length tolerances on a lifted structure.

The major findings of this study are as follows:

1. Division of the load between pairs of slings in a four-sling lift exceeds 80%/20% for loads of relatively low torsional stiffness. A 100%/0% split must be expected with very rigid loads, such as a vessel lifted horizontally by four trunnions.
2. The DNV skew factor typically underestimates the degree of load split and, therefore, yields unconservative analysis results.
3. The API RP 2A load factors ignore the asymmetry present due to inexact sling lengths. Thus, it is possible to underestimate member loads by a great enough factor that, if the structure is designed in strict accordance with the code, a failure could occur.
4. The best way to account for sling length errors in analysis is to model the maximum expected length error using an initial strain input or a thermal load.

It is recognized that design codes and specifications are evolutionary in nature. The documents that address lift analysis procedures should consider the findings reported here and modify their requirements to better reflect the actual behavior of lifted structures and the analysis capabilities commonly available in the engineering office. Until that time, it is incumbent upon the design engineer to recognize and account for this behavior in heavy lift engineering work.

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