Engineering Appraisal of Wheelchair Lifts

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The findings of a continuing study to investigate the design, operation, and maintenance procedures of wheelchair lifts in transportation buses are described. The primary objective is to develop structural design guidelines for rigid platform lifts. Structural design aspects of current wheelchair lift specifications are reviewed, as are the demand conditions that better describe the serviceability and ultimate limit state loads for the design of lift structures. The load demand conditions are determined on the basis of a field investigation of rural transit agencies and a survey of fleet managers, fleet maintenance personnel, and bus drivers. The lift structural performance is evaluated on the basis of a finite element model developed for the rigid platform lift. The finite element model is used for evaluating the structural component deformation and strength supplies of the lift structure under the critical demand conditions. The conclusion includes the evaluation of the structural performance of the rigid platform lift. The numerical data are obtained from a lift structure similar to those used in small and medium-sized transportation buses.

This paper is based on an ongoing study to investigate the design, operation, and maintenance aspects of wheelchair lifts. The goal of the multiphased project is to assess, identify, and resolve the sources of wheelchair lift failures in transit buses. The objective of Phase 1 was to perform a preliminary investigation of the design, operation, and maintenance aspects of wheelchair lifts (*1*). In this phase, manufacturers and fleet managers were surveyed, and a mathematical computer-based model describing the lift was developed using finite element techniques. The mathematical model was used to analyze the structural component strengths and deformation. In addition, the framework of a reliability model was established on the basis of repair data developed with the help of transportation agencies.

In Phase 2, the modeling work (both structural and statistical) was continued in order to refine and calibrate the various model parameters. In this phase, an experimental investigation of the operation of wheelchair lifts was initiated to aid in the development of structural specifications to improve such operation. The Phase 1 report from which this paper is developed addresses the problem identification process designed to examine the serviceability of wheelchair lifts. This process is based on a combination of engineering and statistical analysis that was conducted independently using a computer-based finite element model of the lift's structural system. A statistical analysis of a select sample of lift repair data was conducted for developing a reliability model. A discussion of the results of the entire Phase 1 report is beyond the scope of the paper; instead, the focus is on the modeling effort and structural analysis of the rigid platform lift.

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Wheelchair lifts used in transit buses are categorized with respect to their architecture as active (platform) or passive (folding). The following terminologies defining the lift categories are adopted from the specifications (*2*):

- Lift or wheelchair lift: A lift is a level-change device used to assist transit and paratransit users with limited mobility. The terms "lift" and "wheelchair lift" are interchangeable.
- Active lift: An active lift is one that when stowed may interfere with the use of the vehicle entrance at which the lift is located; when raised and lowered, it operates primarily outside the vehicle. It is also called a platform lift.
- Passive lift: A passive lift is one that when stowed allows the unlimited use of the vehicle door in which the lift is located. It is also called a step lift.

OBJECTIVES

The primary goal of this study is to improve the structural design guidelines of rigid platform lifts. The structural analysis model of the rigid platform lift will be presented, and the current specifications that are the basis of the design of the rigid platform lift will be summarized. Structural design aspects of the current specifications are critiqued, and additional load demand conditions that better describe the serviceability and ultimate limit state actions on the lift structure are described. The lift response to these demand conditions are evaluated using the structural analysis model. The numerical proportions and other structural parameters of the lift structure are acquired from a lift being used in public transportation buses.

STRUCTURAL SPECIFICATIONS

Wheelchair lifts used in small transportation buses are commonly called rigid platform or active lifts. The rigid platform lift requires a special entrance to the bus and consists of the main frame, deployment/actuator assembly, and a platform frame. An example of a rigid platform lift is shown in Figure 1. The specifications pertaining to the lift structural system are covered in various publications (*2,3*). In these specifications the design issues are grouped under design loads for service and ultimate limit states, allowable and maximum component stresses, allowable deformations, and testing and durability requirements. The most comprehensive specification covering these aspects is the primary basis of manufacturers' design specifications (*3*).

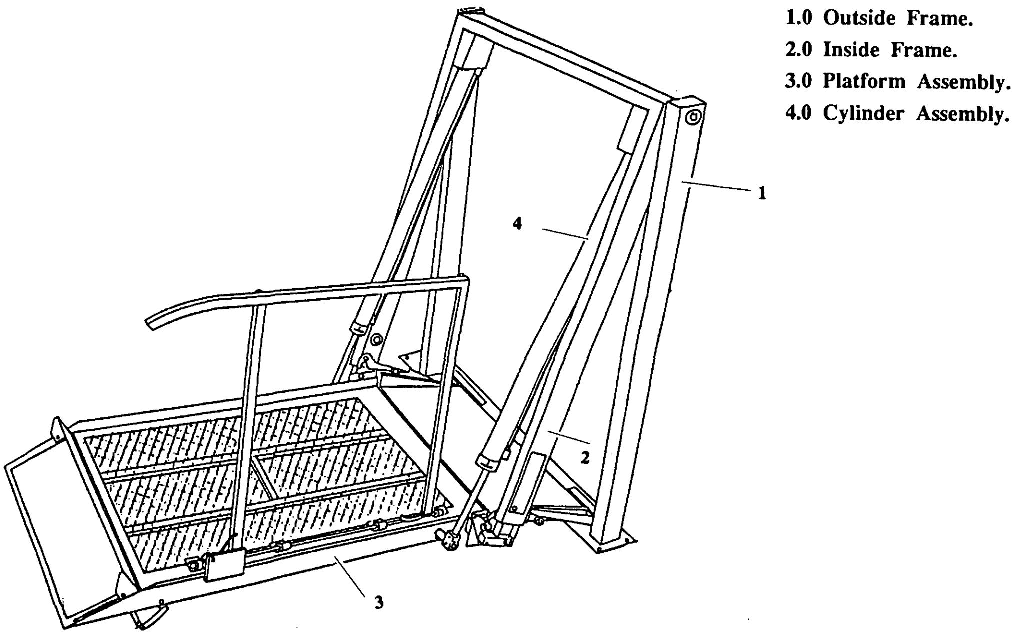


FIGURE 1 Active lift used in transit buses.

The critical design aspects of the lift structural system are as follows (*3*):

1. Lift system self weight is limited to 4450 N (1,000 lbf) for standard buses and 1780 N (400 lbf) for small buses.
2. Service (operating) design load is 2670 N (600 lbf), and ultimate design load is 8010 N (1,800 lbf). Ultimate design load is defined as the load to initiate yielding in any component.
3. Lift service deformations are defined in terms of platform rotations and limited to 3 degrees in any direction.
4. The dynamic actions during lift operation are defined in terms of platform dynamics and limited to 150 mm/sec (6 in./sec) velocity, 0.3 *g* acceleration, and 0.3 *g*/sec jerk.
5. Lift durability is defined as useful life of 12 years and by number of deployment cycles. The durability tests require 10,000 cycles of deployment and 600 operational cycles under 2670 N (600 lbf) followed by 15,000 operational cycles under 1780 N (400 lbf).

STRUCTURAL ANALYSIS

Structural Model

The rigid platform lift (Figure 1) structure consists of three main subassemblies: the main frame, the deployment system, and the platform structure. The main frame consists of two side columns and a common base plate that allows connection to the bus chassis. The deployment system consists of two telescoping members that allow the platform to be raised and lowered. Two hydraulic actuators and two cam brackets that allow the telescoping members to swing forward of the main frame plane are also parts of the deployment system. The platform structure consists of the platform beams, handlebar, and decking.

To bring the lift shown in Figure 1 to full deployment, the dual hydraulic cylinders extend downward approximately 1150 mm (45 in.) to reach the ground. To stow the lift after full deployment, the hydraulic cylinders will retract and fold the platform between the telescoping tube components, upon which the cylinder and sliding tube assembly will swing inward with the assistance of the cam bracket and align with the main frame. The actuators assist in folding the platform and retracting the assembly inside the bus. This motion is achieved by a cam bracket that rotates the platform. During deployment a bridge plate joins the platform with the bus floor, and the platform is held at a semideployed position with two key hinges (also defined as the cam brackets)—one at each end—that allow the platform to rotate 90 degrees.

The geometric properties of the deployment and platform systems are primarily defined by the lift's functional expectations. The wheelchair size that can be accommodated is a function of the platform size, and deployment system geometry is related to the bus's floor clearance from the ground. The rigid platform lift is often used in small to medium-sized transit and paratransit buses. It requires a deployment distance of approximately 1150 mm (45 in.). The platform dimensions vary among different manufacturers and models. In this study, typical platform dimensions of 760 mm (30 in.) wide and 1070 mm (42 in.) long were used.

Component properties and material properties used in the structural model are taken from the lift shown in Figure 1. The model at this stage covers only the fully deployed lift configuration. Other lift configurations, such as fully stowed and semideployed, will be analyzed in future work.

The simplified geometric description of the lift structure is shown in Figure 2. The bridge plate, platform decking, and handrail are deleted from the figure because they do not contribute to the lift's load-carrying capacity. In addition, the key-hinge connections that hold the platform rigidly in deployed position are simplified.

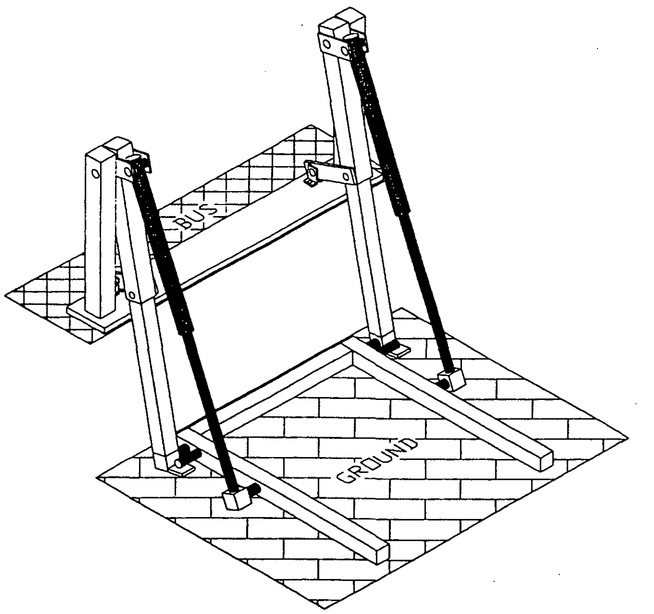


FIGURE 2 Rigid platform lift in deployed position.

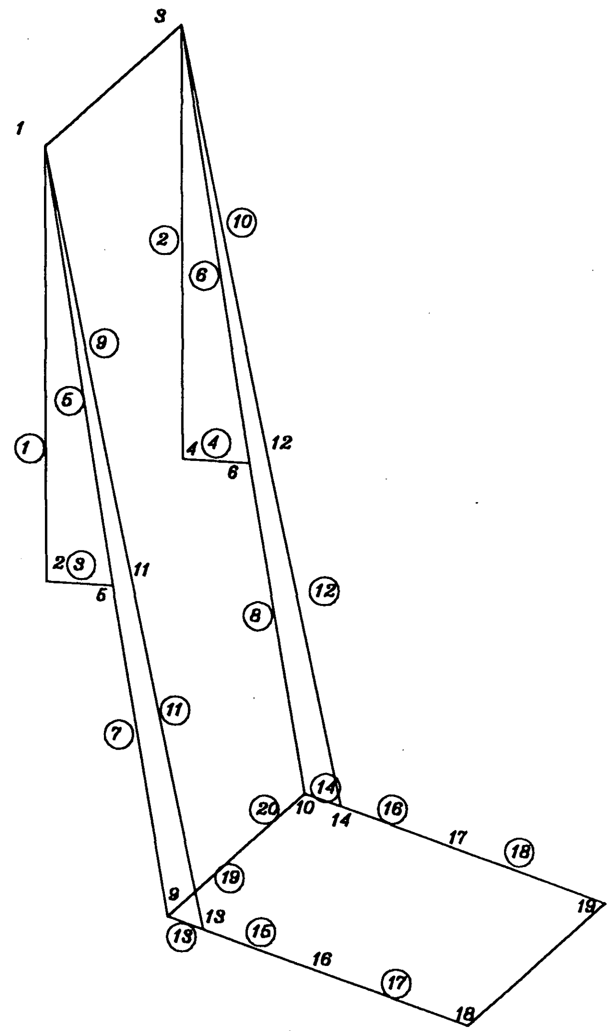


FIGURE 3 Discretized model of fully deployed lift.

Finite Element Model

The finite element model of the lift structural system is developed from the simplified geometry and shown in Figure 3. The nodal coordinates are given in Table 1. Each finite element describes the force-versus-deformation relationship of a portion of structures. In this figure the node numbers are included that designate the element boundaries and connectivity between each element. The structural model is described by seven element groups of two element types; the element types are three-dimensional beam element and three-dimensional truss element. A total of 17 nodes and 20 elements describe the model.

The three-dimensional truss elements are described by cross-sectional area only. The three-dimensional beam elements are described by the moment of inertia with respect to two orthogonal axes with cross-sectional areas. Note the description of the hollow box sections between Nodes 1 through 5 and Node 9 in Figure 3 that telescope during deployment. In these two elements, bending stiffness and, at the joint connecting them, rotational degree of freedom should be present; however, there cannot be any axial stiffness because the components are allowed to slide in and out. This characteristic is modeled by releasing the axial degree of freedom along the axis of the element.

For this analysis the interaction of the lift structure with the bus structure is ignored. The lift frame connections to the bus frame connections are assumed to be fixed.

The element groups, node numbers designating the element boundaries, element indexes, cross-sectional geometry, and geometric properties are given in Table 2. Element Indexes 1 and 2 constitute the main framing, Element Indexes 3 through 12 constitute the deployment system, and Element Indexes 13 through 20 represent the platform structure.

Loading Conditions

During deployment and stowing the lift structure is subjected to static and dynamic loads in addition to the passenger (service) loads. Some examples of these load demands are (a) inertia force on the lift in the stowed position while the bus is in motion, (b) upward force from the ground due to lift overextension during deployment (some active lifts include a ground sensor, but the sensor may be inoperable or the ground uneven), and (c) impact factor when the platform motion is initiated under passenger load. These loading conditions are presented in Table 3.

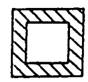
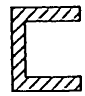
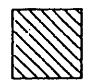
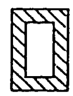
The service level load is increased to 4450 N (1,000 lbf) assuming an impact factor of 1.4, which is a function of rise time and the dynamic properties of the lift structures. The dynamic forces will be converted to equivalent static loads when multiplied with the impact factor. The impact factor is computed using the lift platform velocity of 250 mm/sec (10 in./sec) and a rise time of 0.5 sec to achieve the maximum

TABLE 1 Nodal Coordinates

Node Number	X millimeter	Y millimeter	Z millimeter
1	0	1625.6	762
2	0	0	762
3	0	1625.6	0
4	0	0	0
5	241.3	76.2	762
6	241.3	76.2	0
9	431.8	-1092.2	762
10	431.8	-1092.2	0
11	302.3	152.4	762
12	302.3	152.4	0
13	558.8	-1092.2	762
14	558.8	-1092.2	0
15	431.8	-1092.2	381
16	965.2	-1092.2	762
17	965.2	-1092.2	0
18	1498.6	-1092.2	762
19	1498.6	-1092.2	0

Note: Node numbers 7 and 8 coincide with node numbers 5 and 6.
1 Inch = 25.4 millimeters

TABLE 2 Lift Structural Element Geometry and Properties

Element	Nodes	Geometry	Type	Property
1 2 5 6	1 - 2 3 - 4 26 - 5 27 - 6		Beam Beam Beam Beam	A = 1620 mm^2 I_x = 1061390 mm^4 I_y = 541100 mm^4
7 8	24 - 9 25 - 10		Beam Beam	A = 810 mm^2 I_x = 466180 mm^4 I_y = 124870 mm^4
9 10	20 - 11 21 - 12		Truss	A = 1160 mm^2
11 12	11 - 22 12 - 23		Truss	A = 1030 mm^2
13 14 15 16 17 18	9 - 13 10 - 14 13 - 16 14 - 17 16 - 18 17 - 19		Beam Beam Beam Beam Beam Beam	A = 1290 mm^2 I_x = 141520 mm^4 I_y = 141520 mm^4
19 20	9 - 15 15 - 10		Beam Beam	A = 1290 mm^2 I_x = 264310 mm^4 I_y = 865760 mm^4
3 4	2 - 5 4 - 6		Truss	A = 290 mm^2

1 $Inch^2$ = 645.1 $millimeter^2$

1 $Inch^4$ = 416231 $millimeters^4$

TABLE 3 Load Conditions

Load Index	Load Condition	Configuration	Description
1	Gravity	2@1100 N & 1 @ 2225 N	Service load
2	Platform two beams against ground	2 @ 4450 N	Impact load
3	Platform one beam against ground	1 @ 8900 N	Impact load
4	Platform one beam against ground	3 @ 3100 N	Impact load
5	Platform one beam against ground	2 @ 4450 N	Impact load
6	Gravity	2 @ 2780 N & 1 @ 5560 N	Ultimate load

1 Pound = 4.45 Newton

velocity, which generates an acceleration of 0.05 g, where g is the gravitational acceleration.

In the analysis of the loads when the lift is fully deployed, the loading cases used are service load condition, maximum gravity load to cause first yield of the lift structure, and conditions observed when the lift is overextended to the uneven ground. The loads due to overextension were observed to occur very frequently in the field.

The ultimate limit gravity load specified as 11.1 kN (2,500 lbf) includes impact load. The ultimate load is computed from a factor of safety of 2.5 against yielding required by specifications. More recently, the Americans with Disabilities Act of 1990 (ADA) specifies a factor of safety of 6 for all moving parts of the lift (*4*). The total load due to lift overextension is taken to be 8.9 kN (2,000 lbf) to account for the hydraulic actuators pushing against the ground. This load, acting upward, is moved to various locations of the platform to simulate uneven ground.

The first yield capacity of the lift structure is computed by reanalyzing the structural model under incrementally increasing gravity load until the maximum stress in any component achieves yield strength. The structural analysis of all other load combinations are conducted in combination with the service load condition.

Analysis

The finite element analysis of the lift structural system is performed using the ANSYS computer program (*5*). The analysis output contains the deflections of all nodes, the axial stresses in truss members, and the bending moment shear force and the axial force in the beam members. The member stresses are nominal values. The property of a critical member such as the cam bracket (Members 3 and 4 in Figure 3) changes significantly along its length. For the design of these members, a more refined analysis is required that involves stress analysis using the boundary forces computed from this study. Such analysis will not be covered in this paper.

The finite element analysis of the lift structure is performed for various load conditions for service and limit states. The primary load condition is a combination of passenger and wheelchair weight that is applied as a concentrated load group: 25 percent of the total load applied at the center of each platform edge beam and the rest applied to the center of the platform back beam, all acting downward as shown in Figure 4. All other load conditions to which the lift structure is sub-

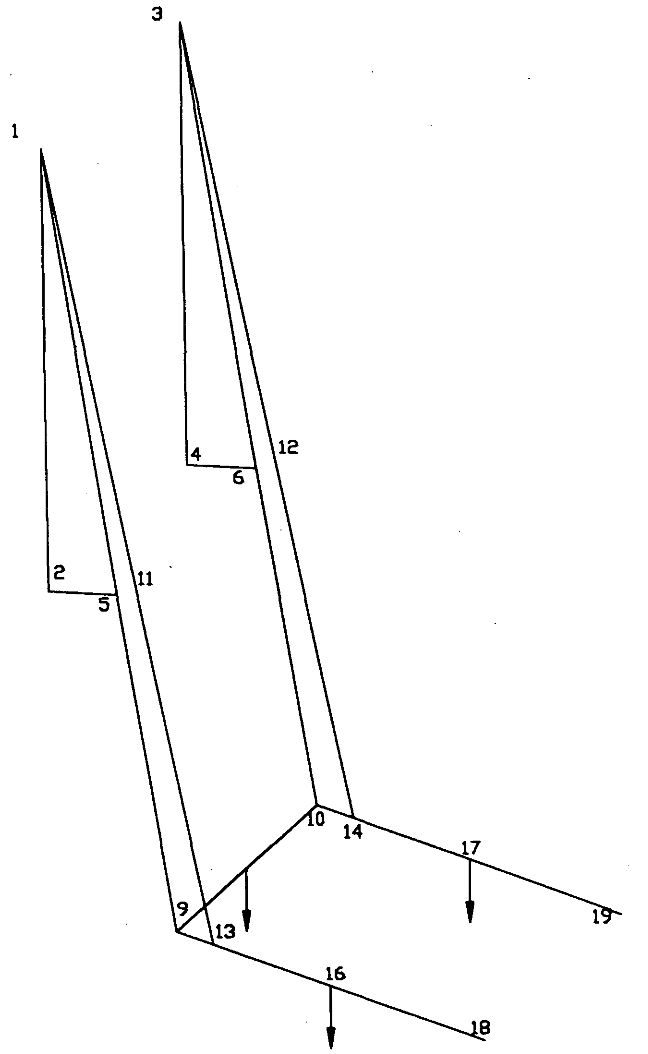


FIGURE 4 Service loading and point of application.

TABLE 4 Load Combinations

Analysis No.	Load Condition
1	1
2	2
3	1+2
4	3
5	1+3
6	4
7	1+4
8	5
9	1+5
10	6
11	1+6
12	7
13	1+7
14	8
15	1+8
16	9
17	1+9
18	10
19	1+10
20	11
21	1+11
22	12

TABLE 5 Nodal Deformations Under Service Load Conditions

Node	U_x millimeter	U_y millimeter	θ_z radian
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5,6	- 0.004572	- 0.000025	- 0.002097
9,10	- 7.597826	- 0.277139	- 0.009526
11,12	- 4.109491	-0.857682	- 0.002798
13,14	- 7.598054	- 1.590599	- 0.011257
15	- 7.600899	- 0.601701	- 0.009526
16,17	- 7.598054	- 7.044868	- 0.014502
18,19	- 7.598054	- 14.780641	- 0.581915

1 Inch = 25.4 millimeter

jected are given in Table 3. The various load combinations are given in Table 4.

The analysis results are presented as nodal deformations and component stresses. The nodal deformations under the service load condition are given in Table 5. Figures 5 and 6 show the element forces in the form of a free body diagram under ultimate level gravity load where the element forces are axial for truss members and axial, shear, and bending moments at end beam members. The component stress computations and the pin shear stresses at various locations of the lift structure and their evaluations are described in the following section.

Evaluation of Results

The analysis results are presented in terms of component forces and stresses for the limit state load conditions. The lift strength performance is checked by computing the component and connection stresses to observe if any structural trauma has taken place. The lift operational performance is verified by checking the maximum component deformations and allowable stresses under the serviceability load case. More specifically, the platform rotation is computed as described in the specification (*3*).

The platform rotation is computed as the average rotation of Elements 13, 15, and 17 (shown in Figure 3). The element rotations are computed from the differential vertical deformations of both ends divided by the element length. Under the service load of 4450 N (1,000 lbf) the platform rotation is calculated as 2 degrees, which is below the 3 degrees specified (*3*).

The critical components of the lift structure are given in Table 6 corresponding to each load combination described in

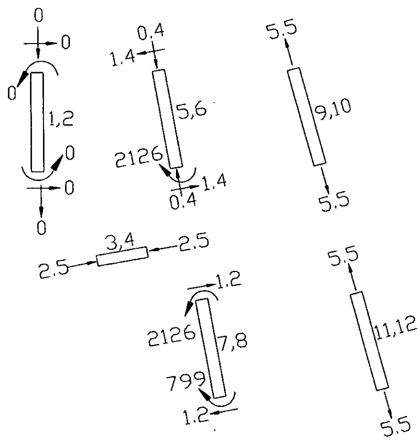


FIGURE 5 Element forces in deployment system components under ultimate level gravity load (moment: kN-mm; force: kN).

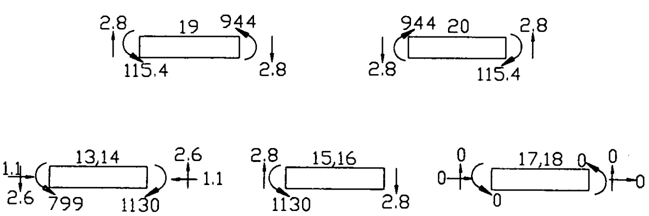


FIGURE 6 Element forces in platform components under ultimate level gravity load (moment: kN-mm; force: kN).

TABLE 6 Stresses of Critical Components

Load Case	Critical Components	Element Stress (mpa) Yield Stress = 344.5 mpa
1	3,4	289.4
2	3,4,13,15,17	344.5
	7	303.2
3	3,4,13,15,17	344.5
	7	275.6
4	3,4	344.5
	13,14	234.3
	15,16	227.4
5	3,4,13,15	344.5
6	3,4	344.5
7	3	344.5
8	3,4	344.5
9	3	344.5
10	3	344.5
11	3,4	344.5
12	3,4	344.5

1 Psi = 6.89 kPa

Table 4. In this table the load condition, the critical components, and a value for uniaxial stress or the yield condition are described. For example, in the service load case (Load Case 1 in Table 4), Elements 3 and 4 (Figure 3) reach a uniaxial stress of 290 mPa (42,000 psi).

A close investigation of Table 6 indicates that various lift components are overstressed even under service load conditions. The critical components 3 and 4 under the service load case correspond to the cam brackets that allow the lift assembly to swing in and out and assist in holding the platform during the stow-away operation. The overload of the cam bracket, shown in Figure 7, was observed during the field investigation. To be more specific, several lifts with rewelded and retrofitted cam brackets were observed during field investigations (*1*).

Other load cases corresponding to ultimate limit state loads also cause very high stresses in some of the lift components, the platform beams indexed on Elements 13 through 18 in Figure 3. Often, component yielding is not observed as noticeable damage. However, repeated yielding of moving parts causes misalignment and general lack of integrity of the lift structure that will lead to operational problems.

Five sets of pins provide load transfer between members. These pins are of different diameters and are located at Nodes 1 through 6 and 9 through 12 (Figure 3). The shear stresses in the pins are shown in Figure 8, evaluated from the free body diagram for all load cases. The shear stresses are higher than the allowable limit. For example, the level of near 68 mPa (9,900 psi) for Pin 4 in Figure 8 is high enough to cause reliability concerns. If the ADA mandate of a safety factor of 6 is adopted in specifications, these stresses should be limited to 15.2 mPa (2,200 psi) for steel with a uniaxial yield strength of 400 mPa (60 ksi) (*6*).

The finite element analysis of the lift structural system provides the deformations of nodes and stresses of the components. Such analysis allows overall understanding of the structural system and identification of problem areas. The study will continue with the experimental investigation of prototype lifts. This will allow the verification and calibration of the analysis model.

SUMMARY AND CONCLUSIONS

A critical review of the specifications for rigid platform lifts is presented. A structural model of the rigid platform lift is developed for evaluating and improving the design specifications. Load conditions are developed to describe the serviceability and the limit state load demands on the lift structure. These load conditions are developed after extensive field investigations and based on the survey of the transit maintenance mechanics and drivers.

Lift structural analysis is performed on a prototype lift structure. The analysis results are described in terms of serviceability deformations and ultimate force demands on the components. From the preliminary investigations and analysis results, it is clear that the lift structural system contains weak links such as the cam bracket and pins. These weak links will be verified during the experimental testing of lifts.

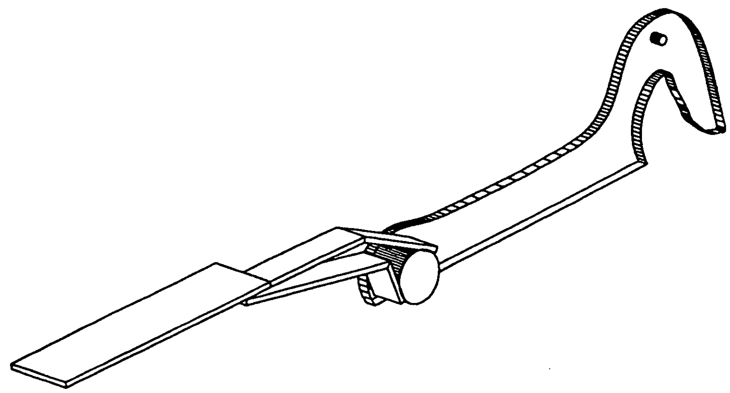


FIGURE 7 Cam bracket connecting middle of inside frame with base of lift.

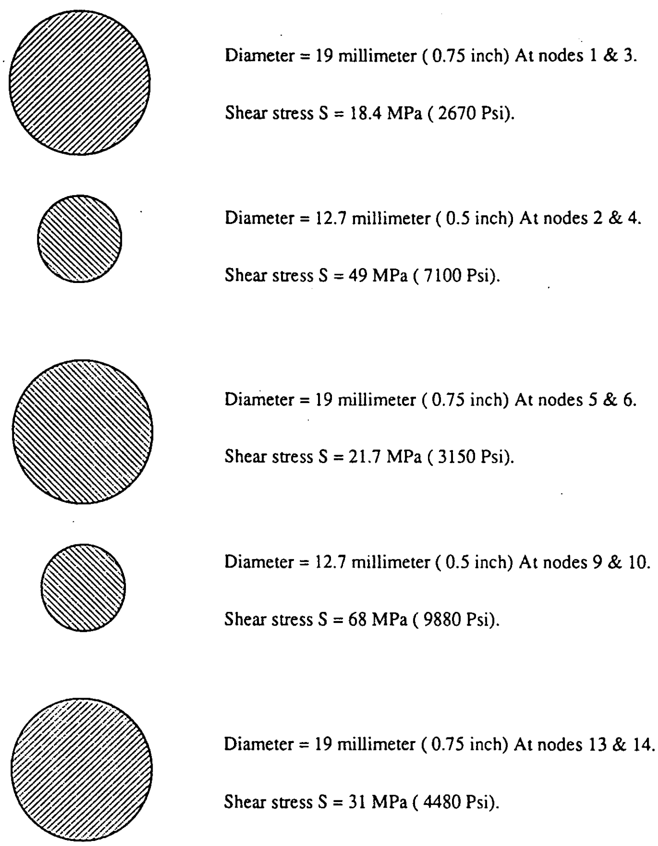


FIGURE 8 Shear in pins under ultimate level gravity load.

The analysis model developed and presented in this paper proved capable of predicting the load path in the lift structure. The weak links identified with the use of this model match our field observation. It is strongly recommended that new load cases be included in the specification. The field investigation indicated that the serviceability and limit state demands on the lift are far different than currently specified, thus lift reliability is compromised by repeated yielding of certain components. Two significant changes recommended for future specifications are to increase the factor of safety and to use the critical load conditions described in this study for the component design.

ACKNOWLEDGMENTS

This study was funded in part by the Michigan Department of Transportation, U.S. Department of Transportation, and Wayne State University. The federal funding is part of the Great Lakes Center for Truck Transportation Research at the University of Michigan Transportation Research Institute. The authors gratefully acknowledge the sponsors for providing the financial support for this study. The final editing and formulation of the paper was done by graduate research assistant Jaiminkumar Pandya.

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