Step Ladder Instability and Dynamic Loading

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Abstract

Step ladders are commonly use for tasks where a human has to reach location 10 to 20 feet high. Although most commercial ladders comply with current standards, thousands of accidents occurred annually due to ladder failure. In many accidents the ladder loose stability and as a result the user falls down and suffers injury. In this paper, a finite element model, which was verified by experimental results, is beng used to analyze common static and dynamic loadings which might cause the ladder to become unstable or fail in some aother way. Finally the finite element model is used to examine the influence of simple changes in the ladder's geometry and material properties to the stability of the ladder.

I. Introduction

Ladders are simple devices which allow the user to reach higher locations that cannot be reached due his height limitations. Ladders are commonly used at home and at work environments by professional and nonprofessional personnel. Various companies offer a range of different types of ladders which include: Step ladders, Extension ladders, Platform ladders, Trestle ladders, Folding ladders and others. Ladders are classified into four types according to the allowed load: Type IA Extra - 300 lbs, Type I - 250 lbs, Type II - 225 lbs and Type III - 200 lbs. Aluminum, timber and fibreglass are the most common materials for ladders.

Safety requirements for those ladders are regulated by the American National Standard Institute (A14.5-1992 [1]). However, some of the tests specified in this standard do not necessarily reflect the way a ladder is being used and are not provide a clear indication whether or not a ladder that passes these test is safe. The fact is that even though most commercially available ladders have passed the specified in this standard, close to 200,000 ladder related accidents which resulted injuries occurr annually [2-6].

This paper describes the development of a finite element model for a 8' step ladder [7]. The model is used to determine the safety of the ladder under various loading conditions. Thus, providing a tool by which static and dynamic loadings can be applied, eliminating the need of costly physical testing. Also, the model can be used to evaluate design and geometry changes.

II. Finite Element Model

A commercial 8 ft type II aluminum ladder was purchased from a local hardware store (see Figure 1). The dimensions of the ladder, all members and the cap were extracted. A finite element model, using ANSYS 6.1, was developed (See Figure 2) [8-12].

The model included the rungs the rails, the cap and the spreaders. . The pail shelf with its side rails was excluded in the model since previous modelling has shown that they do not contribute to the stiffness of the ladder and have no influence on the result.

ANSYS "beam24" element was used for members with rectangular cross-section. ANSYS "beam44" was used for those members where the cross-section had to be pre-defined or sketched. Areas and moments of inertia were automatically calculated by ANSYS. ANSYS " shell63" was used to model the top cap as a shell with a uniform thickness of 10mm, defined by the end-nodes of the four rails.

Figure 1: The aluminum step ladder.

To approximate the flexibility between rungs and rails the rivets, connecting these parts, were modeled by two seperate nodes (one on each part) connected by a revolute joint element (ANSYS "combin7"). This element type allows an additional rotation, in this case about the axis of the rivet. The stiffness of the joint can be varied by changing the real constants of this element, affecting the stiffness of the whole ladder. The real constants of this element determine the translational stiffness along three axes and the rotational stiffness about two axes.

Figure 2: Ladder's finite element model.

Since no exact material properties were available standard values are used. The material of the top cap can not be identified clearly and assumed to be polypropylene. The materials' properties used in the model are listed in table 1.

Table 1: Material Properties.

Part	**Material**	**Young's modulus** $[GP]$	**Density** $[kg/mm^3]$	**Poisson Ratio**
Rails	Aluminum	70	2.7e-6	0.3
Rungs	Aluminum	70	2.7e-6	0.3
Top cap	Poly-propylene	1.5	1.0e-9	0.3
Spreader	Steel	210	7.7e-6	0.3

III. Model verification

In order to verify that the finite element model provides accurate results, few experiments, as specified in ANSI A14.5-1992 were conducted. The experiments results were used to tune the model by changing the stiffness constants of the joint so that the results obtained by the model will match (to some degree) the experimental ones.

Type-I Racking Test

The ladder was set in fully open position and both front feet were individually blocked. A distributed load of 100lb was applied on the bottom step and a vertical pulling force at the top cap to lift the rear feet approximately 3 inches above the floor. Further, a lateral force of 6lb was applied to the rear feet where the displacement was meassured. For this experiment a displacement of 13.5 inches or 343 mm at the rear feet was obtained. This is well below the allowable limit of 18.7 inches for a 8 foot Type-II ladder.

Without the additional rotational joint elements, the finite element model determined a displacement much smaller than in the experiment. To increase the flexibility of the ladder these rotational joints were added. The value for their real constants, which are a meassure for the stiffness, were selected in a such a way that the model's t model matched the experiment results.

Torsion Test

In this test a 200[lb] distributed load was applied at the top cap. A horizontal force of 25[lb] directed to the rear was applied at the top cap at a distance of 18 inches from the center line of the ladder (see Figure 4). Movements of more than 1 inch of the ladder with respect to the floor or any visible damage or weakening after release of the test force constitute failure of this test. Three different loads were usedin this test as shown in table 2.

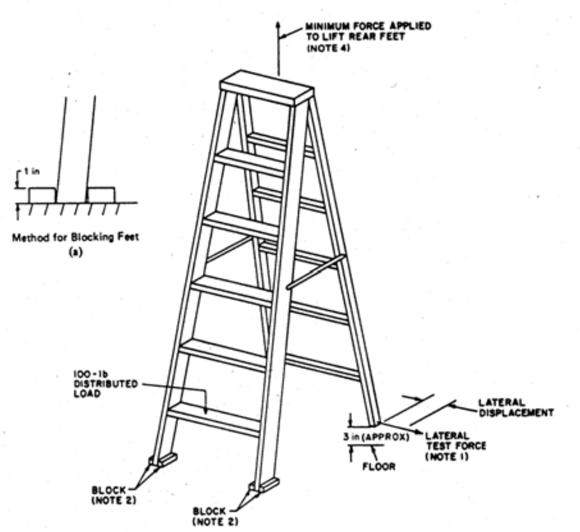

Figure 3: Racking Test according to [1]

Table 2: Results Torsional Stability Test

Horizontal pulling force at cap	Movement of front rail
25 lb	not visible
30 lb	1/2 in
60 lb	3/4 in

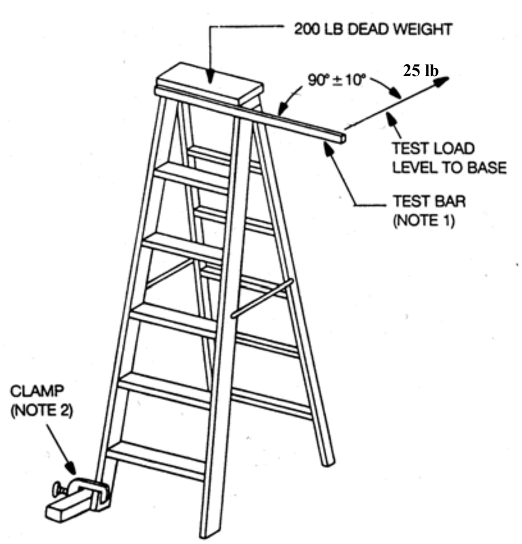

Figure 4: Torsion Stability Test.

Front and Rear Stiffness Tests

In these experiment the stiffness of the front anf thr rear parts of the ladder were tested separately. The ladder was laid on its front (or rear) was clamped at the right rail at the bottom and third steps and at both corners of the plastic top cap. A force directing upwards, perpendicular to the rail, was applied at the bottom of the left front rail. The displacement of the left front foot with respect to the table was measured. The results obtained from this experiment and the model are given in table 3.

Considers the fact that the accuracy of the meassurement is in order of ±0.5mm the values obtained from the model are very good.

Table 3: FEM results for front and rear stiffness

	pulling force [lb]	displacement [mm]		Difference [mm]
		ANSYS	experiment	
Front	6	3.2	2.4	0.8
	10	5.1	4.1	1
Rear	2	1.6	1.5	0.1
	4	3.1	2.7	0.4
	6	4.8	4.4	0.4

Other Tests

In these tests the ladder was put onto its side. The front right rail was fixed at the bottom, spreader and top. In the first experiment a force perpendicular to the rail was applied at the rear right foot, directing towards the front. In the second experiment the pulling force at the rear right foot was pointing upwards, perpendicular to the rail. The displacement of the rear rail with respect to the table was meassured at the joint of rear rail and spreader (See table 4).

Table 4: Results Further Tests

	Pulling force	Displacement
Test I	2 lb	6.8 mm
	4 lb	14.2 mm
	6 lb	21.8 mm
Test II	2 lb	0.6 mm
	4 lb	1.2 mm
	6 lb	2.0 mm

VI. Ladder Instability

There are obvious reasons that will cause ladder instability such as incorrect mounting, overloading, over leaning to one side and others. However the following analysis deals with one particular mode called Type II Racking which most users are not aware of and as a result the ladder might tip causing injuries to the user.

Consider the following scenario: A person mounted a step ladder correctly; meaning all four feet are touching the ground and the ladder is not twisted (see Figure 5a). Then, holding a tool box in his left hand he attempts to climb a ladder. He puts his left foot on the first rung and holds the left rail with his right hand pulling himself up. As a result he applies a twisting torque on the ladder and a horizontal force that might lift the rear foot. These two loads might cause the rear feet to move to the right and the right rear feed to be raised and loose contact with ground. Once the user is on the first rung the magnitude of the horizontal for is reduced but due to friction between the left rear foot and the ground and the increase of the vertical reaction force, the foot does not slide back to its original position. At this instance only three feet (front feet and left rear foot) are making contact with ground. As the user continues to climb the ladder is still stable as long as the center of gravity of the user falls inside the triangle defined by the contact point of the three feet (see Figure 5b).

As the user step up to a higher rung, its center of gravity comes closer to the line A-A (see Figure 5b). Reaching to an object on his righ, or just shifting his weight fro left to right, might locate his center of gravity right to line A-A. At this instance the ladder will rotate to the right (about line A-A) and the rear right foot, which was raised, will hit the ground. As a result, the right rear rail is exposed to impact force that might cause it to fail. In most cases the rail is bent and the as result the ladder collapse and the user falls (see Figure 6). In other cases, the user can loose his balnce and fall from the ladder.

Three experiments were conducted to demonstrate Type II racking. A distributed load of 150[lb] was applied at the bottom step and a horizontal pulling force of 20 [lb] directed toward the front was applied at the joint between the fourth step and the front right rail. The results of these tests are given in table 5.

The ANSYS model at this point predicted displacements five times smaller than the measured ones. Since the stiffness of the front and the rear of the ladder were adjusted earlier, the only adjustment that can still be done is to the stiffness of the cap.

The original model of the plastic cup geometry consisted on a uniform 10 mm thick plate. To increase the stiffness of the cup all was around rib was added, similar to the geomtry of the actual cup. This modification improved the prediction determined by the model. For example, for the first case shown in Table 6 the result obtained by the model were: displacement of 79 mm and raise of 14.2 mm. These are very good results considering the flexability of such a structure.

At this point it is clear that due to the fact that the rear right foot is subjected to an impact load rather than static load. Even for a low impact velocity the load is at least double the static load. Tis failure mode is not addressed in ANSI A14.5-1992 standard and the required tests do not provide any indication for this mode of failure.

Table 5: Results Type-II Racking

Distributed load at bottom step	Horizontal pulling force	Rear right foot Raise	Rear left foot displacement
150 lb	20 lb	15.87 mm	76.2 mm
180 lb	23 lb	25.4 mm	114.3 mm
210 lb	20 lb	25.4 mm	120.6 mm

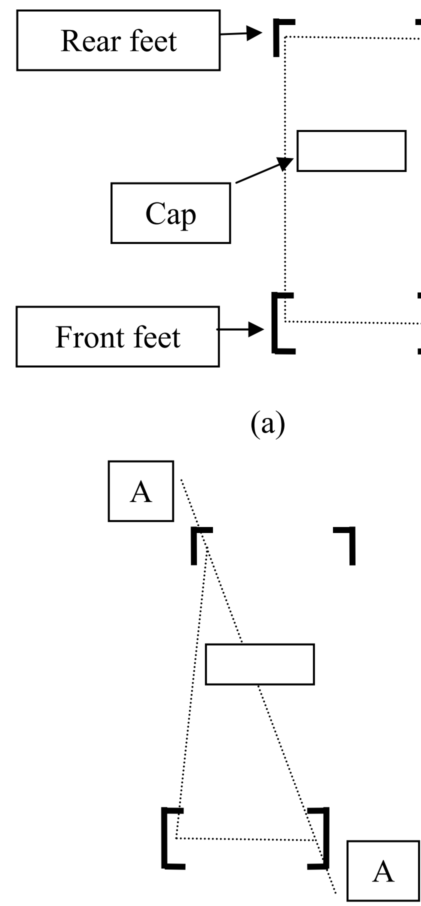

Figure 5: Type II Racking.

V. Dynamic Loading

Dynamic loading of a ladder is very common since the ladder is used to reach a location at which different tasks have to be performed. Simple tasks such as side-to-side overhead painting or cleaning or stoking merchandize on high shelves would cuase dynamic loadind.

As an example an 80 [kg] person standing on the fifth step and performing overhead painting, was considered. It was assumed that 50% of his weight was shifted in the range of ±30°, due to his motions.

Figure 6: Type II Racking failure.

The FE model was used to solve for the feet reactions in increments of 10°, and the results are shown in Table 6. Naturally, the reaction forces between the foot and the ground have to be positive. Thus, a negative reaction force indicates that the foot lost contact with ground. The results shown in Table 6 indicate the contact force on the rear feet alters it sign which mean that a rear foot might loose contact with ground. In this case instability similar to Type II racking might occurrs.

VI. Impact load

In this an impact load was considered. As an example, a case where a person standing on the fourth rung and hammering a nail to the wall in front of him, was analyzed. It is assumed that the user's left hand is using the ahmmer while his right hand is holding the right front rail. A diagram of the forces are shown in Figure 7 where F_1 is the impact force; F_2 and F_3 are forces applied by the user's hand and feet; and F_4 is the user's weight. The distances l_2 and l_3 were determined by the size of 90% male.

A triangular impulse, with a maximum force of 1000N was assumed and was discretized into five loadsteps as shown in Figure 8. The force on the ladder's feet, as determined by the model, are summarized in table 9. As expected, the magnitude of the forces.

Figure 6-7 shows the deformed shape of the ladder for each of the five loadsteps. The reaction forces at the four feet of the ladder are always positive. Their minimum is 5.1N. This means the ladder is standing safely on all four feet over the total time and there should be no saftey risk for a loading like this.

Table 6: Reaction forces for fluctuating load.

Load step	Angle Of force	load on step in X	load on Step in Y	Reaction forces in y-direction on ladder feet	
				Rear right	Rear left
	[°]	[N]	[N]	[N]	[N]
1	0	0.00	-800.0	31.02	35.9
2	10	69.4	-793.9	208.3	**-142.5**
3	20	136.8	-775.8	379.8	**-316.2**
4	30	200.0	-746.4	540.2	**-479.7**
5	20	136.8	-775.8	379.8	**-316.2**
6	10	69.4	-793.9	208.3	**-142.5**
7	0	0.0	-800.0	31.02	35.9
8	-10	-69.4	-793.9	**-146.7**	213.9
9	-20	-136.8	-775.8	**-319.6**	385.9
10	-30	-200.0	-746.4	**-482.3**	546.8
11	-20	-136.8	-775.8	**-319.6**	385.9
12	-10	-69.4	-793.9	**-146.7**	213.9
13	0	0.00	-800.0	31.02	35.9

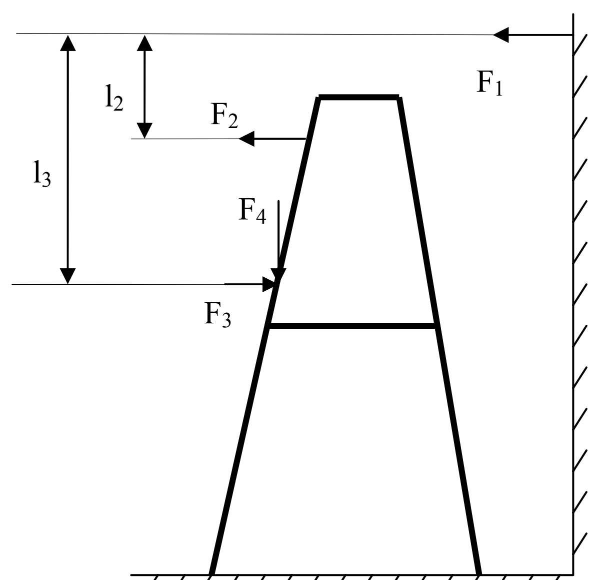

Figure 7: Forces on ladder

VII. Ladder Modification

It is clear that Type-II racking is caused becuase the front of the ladder is not sufficiently stiff to resist twisting torque. In [13] the stiffness of the front rails were doubled and as a result the racking deflection was reduces by 33% with minor reduction in the ability of the ladder to accommodate uneven floor.

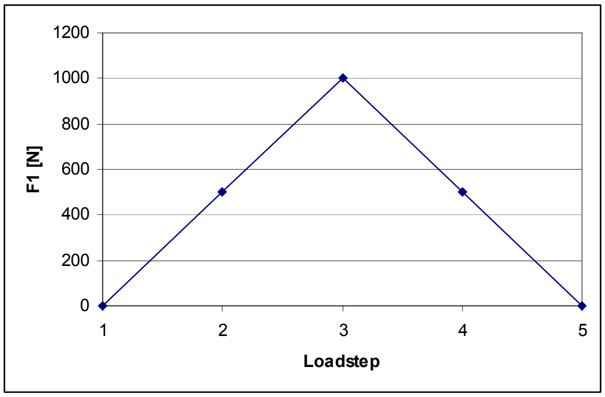

Figure 8: Discretization of the impact load.

Similarily, the FEM model was used to determine the effect of some modifications. The same loads (a vertical load of 150[lb] on the first step and 20[lb] horizonal force to the right rail) were applied for different changes in the propertes or cross-sections of the rails. The lateral displacement of the rear left foot and the raise of the rear right foot were determined. Table 7 shows the resulted displacements for cases where the stiffness of the front and rear rails are increased 200%, 300% and 400% by increasing the Young Modulus of the material and maintaining the same cross-section geometry. As can be seen, the increased stifness of the rear rails does not make a difference in the displacements of the rear feet. On the other hand, as expected, the increase stiffness of the front rails increases the resistance of the front ladder to a twist torque and as a result reduces the deflection of the feet by more then 50% in the best case.

Table 7: Rear feet displacement due to change in E.

Dispplacement [in]	**Original ladder**	**Front rails modification**		
		2E	3E	4E
Left foot	0.48	0.3	0.25	0.21
Right foot	2.54	1.6	1.3	1.17
		Rear rails modification		
		2E	3E	4E
Left foot	0.48	0.44	0.44	0.39
Right foot	2.54	2.52	2.52	2.51

Since the increase in Young Modulus is artificial a more practical approach, from manufacturing point of view was taken. The thickness of the rail profile, *t*, was increased stepwise by 20%. The resulted displacements of the rear feet are summarized in Table 8, which indicate, as expected, similar behavior as in the previous case.

Table 8: Rear feet displacement due to change in *t*.

Dispplacement [in]	**Original ladder**	**Front rails modification**		
		1.2t	1.4t	1.6t
Left foot	0.48	0.43	0.40	0.37
Right foot	2.54	2.25	2.04	1.87
		Rear rails modification		
		1.2t	1.4t	1.6t
Left foot	0.48	0.46	0.45	0.44
Right foot	2.54	2.53	2.52	2.51

One reason the rear feet have large deflection in Type-I racking is that the front and rear parts of the ladder are attached to each other mainly through to top cap. In many implementation the top cap is made of plastic material which makes this connection very flexible. Moreover, the spreaders, attached to the rails with pivots as shown in Figure 8, do not increase the ridity of this attchement since they form a parallelogram that has negligble resistance to lateral force or twisting torque.

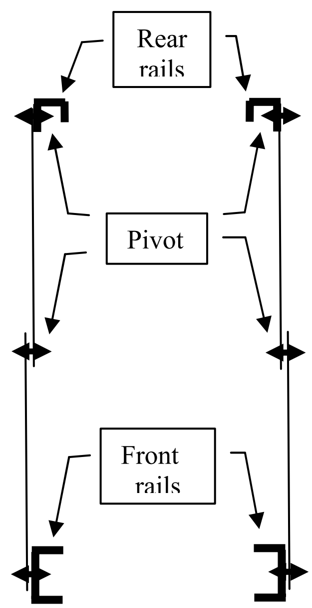

Figure 8: Spreader connection.

To stiffen the connection between the fron and the rear of the ladder it is proposed to modify the spreaders as shown in Figure 9. This “cross shape spreaders“ is by far stiffer than the parallelogram shape mentioned above.

Table 9 provides the deformation results, for the same loading but with thhe modified spreaders. The results indicate that this spreades' arrangement is equivalent to increase the thicknees of the fron rails by 60% (see Table 8) or their stifness by 60% (see Table 7). This is better economical soultion cmpares with the other two.

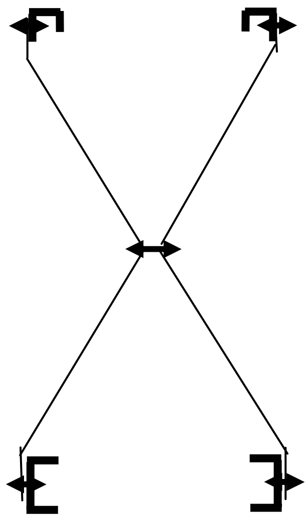

Figure 9: Cross shape spreades.

Table 9: Rear feet displacement for modified spreaders.

Dispplacement [in]	Original ladder	Modified Spreades
Left foot	0.48	0.38
Right foot	2.54	2.24

7. Conclusions

In this paper a finite element model of a step ladder is described. The model was "tuned" to match experimental result and thus the confidance in further studies. Simulation results for dynamic loadings and Type-II racking indicate that the ladder might become unstable even though it passes al ANSI 14.5 standard requirments. Simple modifications for the ladder construction were investigated and the result have shown increase in the ladder stiffness and stability.

VIII. References

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