

Failure of Fiberglass Ladders Due to Manufacturing Defects

Oren Masory

Department of Ocean and Mechanical Engineering
Florida Atlantic University
Boca Raton, FL 33431

Email: orenmasory@gmail.com

Author Note: Dr. Masory earned his degrees from the Technion – Israel Institute of Technology. His interests include: Industrial Automation, Assistive Technology, Accidents Reconstruction and Safety.

Abstract: This paper analyzes the failure of fiberglass ladders due to defects in its rails. These defects were introduced during their manufacturing process in which the fibers are pulled through a resin bath and then through a mold. If the fibers are not fully impregnated with resin and remain dry, a load transfer from resin to fiber cannot take place and hence they cannot support compression loads. As a result, the rail might fail due to high compression stress or due to propagation of a cracks due the voids in the composite matrix.

Keywords: *Ladder failure, Fiberglass ladder, Pultrusion of FGFR*

1. Introduction

According to the Center for Disease Control and Prevention, “Each year in the U.S., more than 500,000 people are treated and about 300 people die from ladder-related injuries. The estimated annual cost of ladder injuries in the U.S. is \$24 billion, including work loss, medical, legal liability, and pain and suffering expenses”. Eventually, some of these accidents are caused due to structural failures and this paper analyzes failures of what is commonly called “fiberglass ladders.”

Glass-fibers reinforce polymer (GFRP) are commonly used for a variety of applications where light weight and high strength are required. Therefore, GFRP are widely used to construct different types of ladders replacing the old wood and aluminum ladders. Two reasons for this change: 1) their light weight and 2) their non-electrical conductivity. The construction of such ladders consists of GFRP rails, metal rungs and cross supports attached to the rails by rivets.

The rails, designed to support compression and bending, are fabricated by pultrusion process. In this process, shown schematically in Figure 1, unidirectional fiberglass roving is pulled along their axis, through a resin bath, impregnated by the resin, and then through a heated die which determines the rail shape. To provide support to lateral loads, a reinforcement mat is embedded between two layers of the fibers. A surfacing veil is embedded on both sides of the rail's surface for better appearance (Figure 2).

Different failure modes of composite materials have been discussed in numerous publications. However, the ones that directly refer to pultruded GFRP will be mentioned in the following.

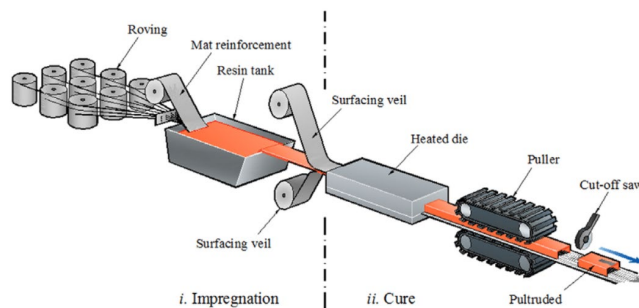


Figure1. The pultrusion process

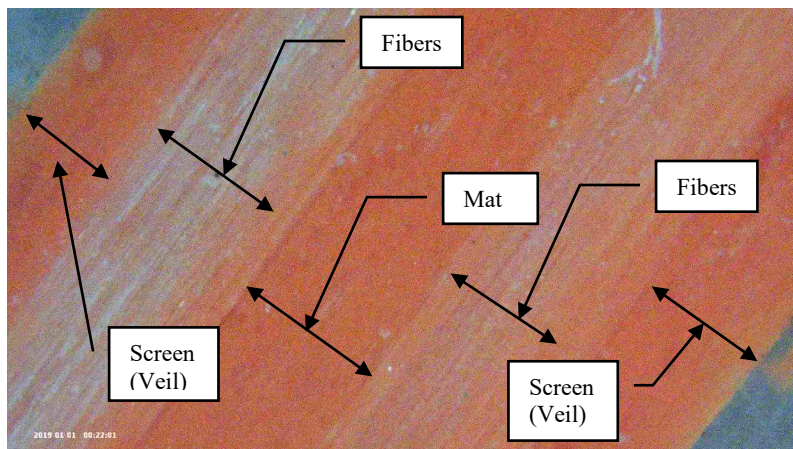


Figure 2. Pultrusion cross-section

This paper discusses some of the causes of the failure related to manufacturing defects of ladders. Two examples are given in the following. Although the details relate to these particular ladders, the same issues might be present in any other fiberglass ladder.

2. Failures Description

Extension Ladder Failure: A 24' fiberglass extension ladder type 1AA with load capacity of 350[lb] was used with extended length of 18.6ft. (Out of 21' maximum working length). A 195[lb] male, was performing an ordinary task while standing on the fifth rung from the top. Once he completed his work, he started to step down the ladder and when he stepped on the 6th rung from the top, the rails of the extension broke just below the 7th rung (Figure 3).



Figure 3. Failure of the extension ladder's rails

Step Ladder Failure: A 150[lb] worker was climbing a new 300[lb] capacity 12[ft] fiberglass step ladder. While standing on the 10th rung, the rear right rail of the ladder broke (buckled, failed). (Figure 4).

Analysis of both cases resulted in stress levels below the requirement specified in ANSI A14.5-2000 standard. Thus, it was concluded that the failures were due to local irregularities in the GFRP extrusion due to the manufacturing process or damage caused by inappropriate use or during transportation. Close inspection of the rails at the proximity of the failure locations did not reveal any external damage.

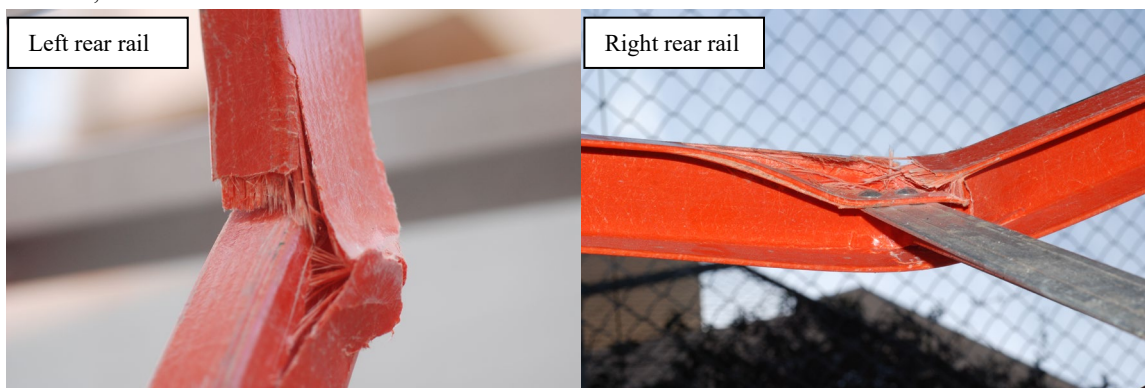


Figure 4. Failure of step ladder's rails

3. Manufacturing Defects

3.1 High Fiber Volume Fraction

As mentioned above, the rails are produced by a pultrusion process in which the fibers are impregnated with resin by pulling them through a resin bath. Then the fibers pass through forming and curing dies where the shape of the rail's cross-section is set. One of the defects associated with this process is poorly wetted fibers which means that some of the fibers were not embedded with resin during their travel through the resin bath. As a result, these fibers cannot carry compression loads (just the same as a cable). Thus, the capacity of the rail to support compression stress is reduced.

Further inspection of the fracture site revealed strands of "dry" fibers at the failed cross-section (Figure 5). These dry fibers can be identified by their white color since they were not wetted by the colored resin. This defect is caused by high fiber fraction (Shakaya et. al. (2016); Binshan et. al. (1995); Abdalla et. al. (2008)) which is the ratio of the fibers' volume to the total volume of the composite. High fiber volume ratio means that the fibers are so close to each other that the resin cannot penetrate and wet all of them. Accepted values for fiber volume fraction range from 50%-60%. For verification, samples were cut from web and the flange of rails in proximity to the failure and were tested according to ASTM D2584-2011. The results, shown in Table 1, indicate the fiber volume ratio in both cases was high, causing the failure.

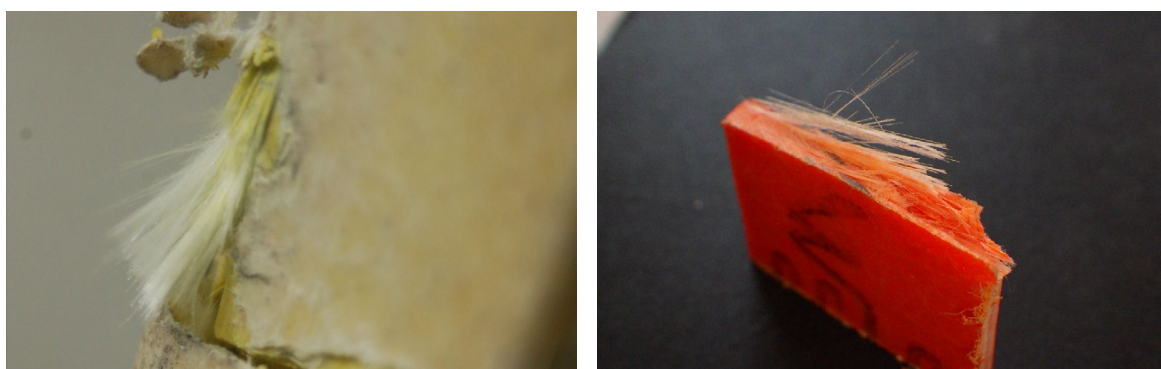


Figure 5. Dry glass fibers

Table 1. Fiber volume [%]

<i>Sample</i>	<i>Step Ladder</i>	<i>Extension Ladder</i>
Web	60.8	71.46
Flange	58.4	73.86

In addition, a strand of dry fibers can cause a separation between the flange and the web (Figure 6), reducing the area moment of inertia of the cross cross-section by almost half. This causes an increase of bending stress by a factor of two and reduces the critical buckling force the same. Also, it can propagate as a crack along the rail with this effect.

3.2 Voids

“In Liquid Composite Molding processes (including pultrusion), there are several causes for void formation such as mechanical air entrapment during resin flow (main cause), gas created due to chemical reactions during cure, and nucleation of dissolved gases in the resin. The air entrapment is mainly due to the inhomogeneous fiber architecture, resulting in non-uniform permeability of the fiber preform, which causes local variation in resin velocity. This local velocity variation is exacerbated by the capillary effect, prevailing at the micro-scale” (Manhoor et. al, (1991); Weiguo et. al, (2012); Little et. al. (2012); Saenz – Castillo (2019)). The effect of the voids is a local stress concentration and crack formation/separation that might lead to a failure (see Figure 7).

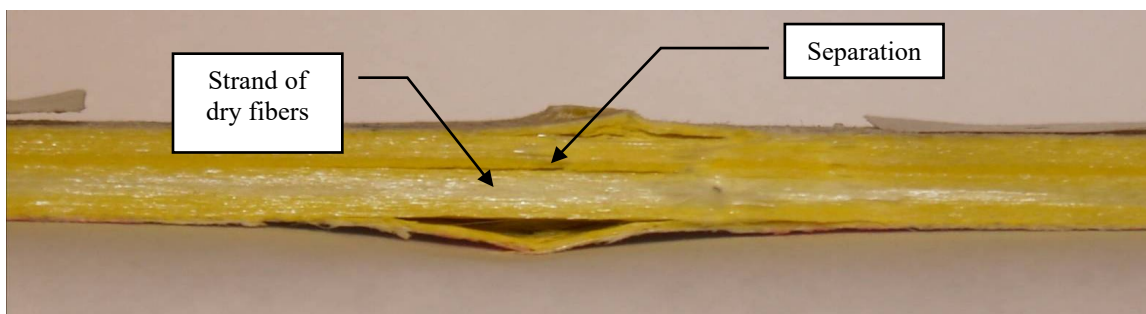


Figure 6. Separation due to dry fibers

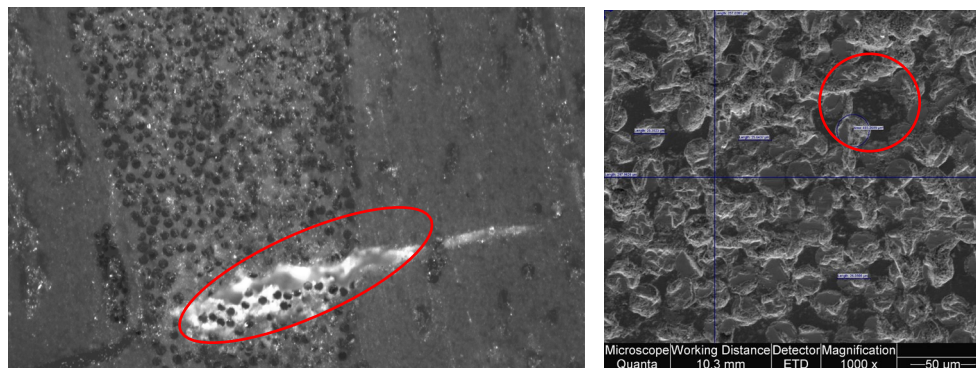


Figure 7. Voids

3.3 Other defects

There are manufacturing defects like: cracks due to machining (e.g. drilling holes for rivets, see Figure 4); broken fibers; fiber waviness; stress concentration due to holes (Abdalla et. al. (2014)). These will be discussed here since they are difficult to detect after the failure.

4. Investigating ladder's failure

In cases of injury due to a ladder's failure, an investigation is initiated before a legal complaint is filed. In these cases the investigator seeks the causes of the failure. Besides obvious reasons such as over loading, ladder misuse (such as wrong mounting, shifting weight), the investigator has additional tools, although limited, to use:

- a. Visual Inspection: Search for manufacturing issues like missing rivets causing a weakness of the structure, missing part such as rubber pads at the bottom of the rails and other.
- b. Fiber Volume Fraction: if a strand of dry fibers are exposed at the fracture location, a sample, as close as possible to the fracture, has to be taken and tested.
- c. Void Samples: as close as possible to the fracture, samples should be taken and the cross section observed under a microscope to determine if there are voids in the pultrusion.
- d. Mechanical Properties: samples of different sections of the cross section (for example web and flange) should be tested for mechanical properties: flexural strength; flexural modulus; tensile strength; tensile modulus; compressive strength; compressive modulus; ultimate bearing strength and impact. All should comply with the minimum values specified in ANSI 14.5-2000. Out of these tests, the compression test is the most important since the compression stresses are the most dominant. Also, the compression test should be performed according to one of the following standards: ASTM D6641 -2001, ASTM D3410/D 3410M – 2003, ASTM D 5467 – 1997.

It is important to emphasize that failures are initiated by local defects, and as a result, the mechanical properties found by the above tests are not necessarily an indication of the properties at the failure cross-section since they might not have the defects that caused the failure. Moreover, there is no way to determine the mechanical properties at the fracture since the defect that caused the failure was destroyed in the process. Also, in most litigation cases failure evidence is not available. Therefore, the best one can do is to use samples which are as close as it is allowed to the location of failure.

Along these lines, samples from both ladders were sent for compression tests (Tables 2 and 3). As shown the maximum compression stress of the extension ladder's sample did not comply with ANSI requirements. The samples from the step ladder were taken from the same rail and the distance between samples was less than 2 feet. In spite the proximity of the samples:

- a. The maximum sustained compression stress of sample 1 are 21% higher than those of sample 2.
- b. The compressive modulus of sample 1 is 51% higher than the one of sample 2.

This large deviation in the properties is a clear indication of inconsistency in the manufacturing process.

Table 2. Extension ladder - Compression tests' results.

Sample	Max. Stress (psi)	ANSI Requirement [psi]
Web	22,100	28,000
Flange	48,300	40,000

Table 3. Step ladder - Compression tests' results of flange samples.

Sample	Max. Stress (psi)	Comp. Modulus [Msi]	ANSI Requirements [Msi]
1	72,600	4.58	2.8
2	59,800	3.06	2.8

5. Quality control and inspection

To reduce the above defects and others, tight quality control during the manufacturing process is the only way. Manufacturers who want their product to be ANSI certified should follow the quality control procedure specified in ANSI A14.5 section 7.13 and Appendix C. It establishes Acceptance Quality Limit (AQL) procedures based on the ANSI/ASQ Z1.4 standard (came after MIL-STD-105E).

As an example, consider a lot of 250 rails that were produced by the pultrusion machine. For a single sampling plan assuming normal distribution, inspection level II and Acceptance Quality Level of 4%, 32 rails must be selected randomly out of this lot and tested. If 3 or less of the samples failed the tests, the lot is accepted; if 4 or more failed, the test the lot is rejected. As AQL decreases, the pass/fail criteria tightens. For example, for AQL=2.5% only 2 (or less) rails can fail in order to accept the lot and if 3 (or more) rails failed, the lot is rejected.

AQL=4% is commonly used for consumer products ensuring that the lot has 0 rails with critical defect, 2.5% with major defects and 4% with minor defects. The question is whether or not a ladder can be considered a consumer product since it is used in work rather than the home environment. If not, the ANSI standard has to be more specific and dictate the required level of AQL.

Pultrusion is the first process in the manufacturing of ladders, which might introduce other defects, for example drilling. In the case of the 12-foot ladder, each of the rear rails has over 20 holes to support the cross members, the footing, and the cap (front rails have more holes). Once the rail is loaded, stress concentration is developed around the holes, and the presence associated of manufacturing defects (such as cracks), can cause the failure of the ladder. Even though it was not specified by ANSI standard, it seems reasonable that rails should go through some inspection after the drilling operation and before the assembly.

6. Conclusions

In the failures discussed, the ladders' rails failed due to being manufactured by pultrusion process. All failures initiated by a local defect so, in most cases, measurements of the mechanical properties of the material, even in proximity to the failure, might not reveal the problem. Detection of possible defects due to the process is possible by microscopy to detect voids or by measuring fiber volume fraction to detect dry fibers. Other manufacturing defects such as cracks due to drilling are very difficult to reveal after the failure.

The only way to reduce, not to eliminate, these defects is by establishing very tight quality control procedures in every step of the manufacturing process. These procedures must be specified by new or modified standards. Thus, manufacturers who advertise their products as compliant with the new standard must adopt it.

7. References

- Abdalla F. H., Megat M. H., Sapuan M. S. B.B. Shari, (2008). "Determination of volume fraction values of filament wound glass and carbon fiber reinforced composites", *ARPN J. of Engineering and Applied Sciences*, Vol. 3, No. 4, August 2008.
- Abdalla M. Abdalla¹, Ahmed Abdel-Moneim¹ & Mohamed N. A. Nasr, (2014). "Modelling Stress Concentration Effects in Unidirectional Glass Fibre-Reinforced Polymer Composites", *International Journal of Engineering Research & Technology (IJERT)* Vol. 3 Issue 8, August – 2014.
- ANSI A14.5 – 2000 American National Standard for Ladders – Portable Reinforced Plastic – Safety Requirements.
- ASTM D6641- 01 Determining the compressive properties of polymer matrix composite laminated using CLC test fixture.
- ASTM D3410/D3410M – 03 Compressive properties of polymer matrix composite materials using with unsupported gage section by shear loading.
- ASTM D 5467 - 97 Compressive properties of unidirectional polymer matrix composite materials using a sandwich beam.
- ASTM D2584-11 Standard test method for Ignition Loss of Cured Reinforced Resins.
- Binshan S. Ye, Alrik L. Swenson, Lawrence C. Bank, (1995). "Mass and volume fraction properties of pultruded glass fiber reinforced composites", *Composites* Vol. 26, 1995.
- D. Saenz-Castillo, M.I. Martín, S. Calvo, F. Rodriguez-Lence A. Güemes, (2019). "Effect of processing parameters and void content on mechanical properties and NDI of thermoplastic composites", *Composites, Part A* 121 (2019).
- John Eric Little, Xiaowen Yuan, Mark Ian Jones, (2012). "Characterisation of voids in fibre reinforced composite materials", *NDT&E International*, 46 (2012).
- Mahoor Mehdikhani¹, Larissa Gorbatikh¹, Ignaas Verpoest and Stepan V Lomov. (1991). "Voids in fiber-reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance", *J. of Composite Materials*, 0(0) 1991.
- N,S. Shakaya, J. A. Roux, A.L. Jewani, (2016). "Effect of fiber volume faraction in fibre reinforced compaction in resin injection pultrusion process", *Polymers & Polymer Composites*, Vol. 24, No. 1, 2016.
- Weiguo Hou, Weifang Zhang, (2012). "Advanced Composite Materials Defects/Damages and Health Monitoring", 2012 Prognostics & System Health Management Conference (PHM-2012 Beijing).

