SANDIA REPORT
SAND2013-3956
Unlimited Release
Printed May 2013

Test Plan: Reducing Soft Costs of Rooftop Solar Installations Attributed to Structural Considerations

Stephen F. Dwyer, PhD, PE

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2013-3956
Unlimited Release
Printed May 2013

Test Plan: Reducing Soft Costs of Rooftop Solar Installations Attributed to Structural Considerations

Stephen F. Dwyer, PhD, PE
Geotechnology & Engineering Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0706

Abstract

This test plan is a document that provides a systematic approach to the planned testing of rooftop structures to determine their actual load carrying capacity. This document identifies typical tests to be performed, the responsible parties for testing, the general feature of the tests, the testing approach, test deliverables, testing schedule, monitoring requirements, and environmental and safety compliance.

CONTENTS

1. Introduction 7
2. Literature Review 8
3. Work Scope 8
4. Schedule of Testing Activities 9
5. Criteria 10
6. Personnel 11
7. Facilities 11
8. Tests to be Performed 12
a. Rafters 12
b. Trusses 14
9. Test Results 16
10. Environmental, Safety, and Health (ES&H) Requirements 18
11. References 18
Distribution 19

FIGURES

Figure 1. Testing Laboratory 12
Figure 2. Point Load on Single Member Test Configuration 13
Figure 3. Point Load on Composite Test Assembly 13
Figure 4. Uniform Load Applied on Test Configuration 14
Figure 5. Uniform Load Applied to Space Truss 15
Figure 6. Uniform Load Applied to Flat Space Truss 15

TABLES

Table 1. Schedule of Testing Activities 9
Table 2. Point Test Results 17
Table 3. Uniform Load Test Results 17

1. Introduction

Today's building codes [ASCE7-10, IBC 2009] are conservative, with a hierarchy of factors of safety. Building codes were first developed in the United States in the 1770s by George Washington and Thomas Jefferson to address size and safety issues. From this beginning, building codes developed primarily at the local level. Cities and/or states would successively increase the level of safety in response to catastrophes such as the Chicago fire in 1871 and the San Francisco earthquake in 1906. Along the way, many code administrations were instituted. It was not until 2000 that most of these independent organizations finally merged to form the International Building Code (IBC). The IBC references key documents and/or bodies of information. For structural loading and compliance, the IBC adopts conservative versions of the ASCE Committee 7 "Minimum Design Loads for Buildings and Other Structures" requirements [ASCE7-10]. Although many local jurisdictions still have their own building codes, most of these codes have adopted the IBC for consistency and to save on the cost of maintaining a work force to develop a more specific local building code.

An identified market barrier to rooftop solar photovoltaic (PV) installations involves structural obstacles in adhering to applicable building codes in the construction permitting process. The city of Madison, Wisconsin identified the obstacle presented by the construction building permit process as their number one market barrier. Virtually all of the cities involved in the Solar America Cities program agreed that structural concerns created major market barriers in the issuance of building permits for new solar rooftop installations in their respective cities.

Based upon our experience as well as input from practicing engineers, solar installers, and building code officials, it is estimated that over eighty percent of existing residential rooftops do not meet the most common current structural code (ASCE 7-10 and IBC 2009) requirements, even before PV panels are installed. This is in part due to the conservatism of structural codes, but more so due to the engineering methodology utilized in evaluating existing roof structures. Customary engineering methods of analysis assume that rafters, joists, and trusses act alone to carry rooftop loads. This is an oversimplification: in fact a roof framing system is a very indeterminate structure. Roof analysis is further complicated because the primary building material is typically wood, which has a wide variety of structural properties depending on its classification, species, condition, use, size, moisture content, and so on. Thus, engineers tend to oversimplify and be very conservative in their analyses. Thus, the lack of load carrying capacity for many houses is a 'perceived' issue rather than a 'real' issue.

Our scope of work addresses this structural market barrier to rooftop solar installations and with successful data acquisition should eliminate it. The outcome should dramatically allow for the increase in the number of rooftop PV installations and reduce permitting and installation costs by:

- addressing current market barriers due to structural issues;
- developing standardized designs and roof structure reinforcement techniques;
- reducing the permit application time and associated soft cost; and
- eliminating the need for a structural engineer's approval on a case-by-case basis for the vast majority of new residential rooftop installations.

This specific test plan outlines the production of empirical data proposed to help overcome the described structural market barrier. Planned work includes:

1. Test roof members and composite structures to determine their actual load bearing capacity.
2. Calculate the load bearing capacity based on applicable national structural regulations (i.e. ASCE 7-10 and National Design Specification for Wood Construction).
3. Compare the actual capacity to the calculated capacities.

The Department of Civil Engineering at the University of New Mexico (UNM) is a key partner with Sandia in performing testing and development of a potential new standardized design and/or structural retrofit techniques for solar rooftop installations. The university recently completed construction of a new engineering complex that houses a new structural testing laboratory. Sandia and the university have performed some preliminary and simplified testing in it to validate the techniques prior to moving toward the larger-scale test program described in this proposal.

The testing program will include testing of scaled rooftop members and composite structures of varying sizes and geometries to compare their actual load bearing capacities to those computed according to the IBC [IBC 2009]. The SunShot recommendation of using existing housing construction periods will be considered in the tests to be performed. Sandia anticipates generating defensible empirical data that will enable the permitting of many of the current applications that are disallowed due to inadequate 'perceived' strength of the existing roof structure.

2. Literature Review

A literature review was performed to ascertain information about composite strength of rooftop structures. This literature review was formalized in the document titled: Literature Review: Reducing Soft Costs of Rooftop Solar Installations Attributed to Structural Considerations. Sandia Report number SAND2013-2090, by SF Dwyer, printed March 2013.

3. Work Scope

A series of tests will be developed and executed to elucidate the structural behavior of common roof structures. The most common roof structure types combined with the historical construction practice and material use will be evaluated in the testing program. Scaled roof structures will be tested to failure. This empirical data or 'actual' load carrying capacity will then be compared on a structure–by-structure basis to the respective calculated load carrying capacity based on the current IBC and ASCE 7-10. It is anticipated that the 'actual' load carrying capacity is significantly larger than the "code" capacity of the same structure. This work will reveal the excess actual load bearing capacity compared to the calculated capacity. This work is scheduled to be performed in FY13 and FY14. All testing is expected to be complete by the end of FY14.

4. Schedule of Testing Activities

Table 1. Schedule of Testing Activities

Task Number	Item Description	Milestone	Start Date	Planned						End Date
				2013				2014		
				Q1	Q2	Q3	Q4	Q1	Q2	
1.0	Testing of Roof Structures									06/30/14
1.1	Finalize test plan	Test Plan Report	10/01/12	X	X	X				06/30/13
1.2	Design actual tests	Test Plan Report	10/01/12	X	X	X	X	X	X	06/30/14
1.3	Initial tests to validate testing concepts	Test Preparation	01/01/13	X	X	X				03/31/13
1.4	Testing of Roof Structures. - Task 1(a) rafter structures to be performed first followed by Task 1(b) truss supported roof structures.	Test Report	04/01/13		X	X	X	X	X	06/30/14
1.5	Compile Test Results	Test Results	04/01/13		X	X	X	X	X	06/30/14
1.6	Calculate load bearing capacity of test specimen based on applicable codes	Calculated Results	04/01/13		X	X	X	X	X	3/31/15
1.7	Include comparison of actual load bearing capacities from testing with calculated values and include in updated Structural Guidance	Release data	07/01/13				X	X	X	3/31/15
1.8	Evaluation of testing progress & evaluation of actual load carrying capacity to calculated load bearing capacity	Go/No Go decision	01/01/14					X	X	03/30/14

5. Criteria

All structural wood design for load supporting wood members, their bracing and connection systems, shall conform to the requirements set forth in the National Design Specification (NDS) (2012) for Wood Construction, including supplements.

Conceptual maximum spans will be computed based on standard engineering principles for simple span beams with uniform loads. It is assumed that at least three joists or rafters will be located next to each other and spaced no more than 24" on center. The calculations will also assume fully supported members that are properly sheathed, with sheathing nailed to the top edge of the joist or rafter.

The horizontal projected distance from face to face of supports in feet and inches defines the maximum spans provided in the tables. This represents the actual length of roof rafter or support. For sloping rafters, the span is also measured along the horizontal projection. The actual rafter length will be calculated based on the slope of the member.

Wood has the ability to carry greater loads for short loading durations. Design values for the lumber used to calculate the maximum spans apply to normal loading conditions and may be multiplied by a load duration factor (CD). This factor is covered in detail in the NDS and is permitted to be used by established engineering design criteria and building code regulations. Floor and ceiling joists are based on the normal ten-year load duration and have a CD of 1.0. Rafters typically have a CD of either 1.15 for two-month duration (snow loads) or 1.25 for 7-day duration (construction loads). This overstress of a calculated wood value is allowed by code for short direction loads such as wind for up to 25%. The testing program will develop results to show what the actual load carrying capacity is for these short duration loads.

Lumber Dimensions:

Lumber size is typically referenced by its nominal size, e.g. 2x4.

Deflection:

These deflection limits are provided for reference only and will not be utilized for calculation or prediction of load carrying capacity. Typical deflection limits apply to prevent aesthetic damage to ceiling (cracking in sheetrock) or minimizing the “bounce” factor for residential construction. Deflection limits are expressed as a fraction of the span length in inches. These limits are generally applied only to the live load criteria, following standard engineering practice for the design of joists and rafters. Typical deflection limits include:

- Floor joists l/360
- Ceiling joists l/240
- Rafters with a drywall ceiling l/240
- Rafters with no finished ceiling l/180

Bending:

Each member is spaced a maximum of 24" on-center and fully supported with properly applied sheathing attached to the top edge of the joist or rafter. The repetitive member factor, CR, of 1.15 will be included in calculations. The load duration factor, CD, will also be included in the calculations.

Horizontal Shear

Horizontal shear rarely controls the spans shown in these tables except under heavy live load conditions (i.e., 60 psf or greater). However, a shear check will be performed using the allowable shear stress values. A shear stress factor, CH, of 1.5 will be employed.

6. Personnel

The team is comprised of Stephen F. Dwyer, PhD, PE, principal member of technical staff with Sandia National Laboratories, and Walter H. Gerstle, PhD, PE, UNM Civil Engineering Department. Dr. Dwyer has developed an expertise over the past three years in structural elements of solar installations. Dr. Dwyer has key industry contacts and has earned a quality reputation. Dr. Gerstle developed the racking systems for UniRac, Inc. and for Array Technologies, Inc., currently available on the market, and has consulted as a structural engineering in the solar energy field as a private consultant in over 200 projects. Dr. Dwyer and Dr. Gerstle have previously collaborated on research and structural testing. Dr. Dwyer and Dr. Gerstle collaborated on a project for the Bureau of Land Management to resolve a safety and risk issue between the oil and gas industry and mining industry. The work involved testing of the structural capacity of oil and gas well casing and deformation characteristics given the potential for differential settlement from nearby underground mining activities. This work was instrumental in defining safety distance between the two industries. Dr. Dwyer and Dr. Gerstle also collaborated on initial solar rooftop structure testing by evaluating the added strength of a rafter by inclusion of the overlying sheathing. Additionally, graduate students in structural engineering will be utilized to assist with all testing activities.

The team will also add marketing and business expertise to assist with the rapid dissemination of data and the rapid adoption of this data by the solar community to eradicate the structural market barrier as soon as possible.

7. Facilities

Testing will be performed at the structures laboratory in the Civil Engineering Department at University of NM. Through previous testing activities, we have developed a workable and efficient testing and monitoring program at this laboratory. Furthermore, we have access to high quality graduate civil engineering students who will provide efficient and cost effective work while gaining an opportunity to pursue viable research topics for their respective degrees. The

University of New Mexico has an environment, safety and health plan in place for this test facility. Additional environmental and safety permits have been issued through Sandia as described in Section 10 of this test plan.

Figure 1. Testing Laboratory

8. Tests to be Performed

Multiple tests will be performed on roof rafter and truss structures to determine the load bearing capacity of varied members and system configurations. Tests will evaluate the rafter/truss individually and then grouped with sheathing connection between rafter/trusses (composite action).

a. Rafters

Initial tests will include a point load application. Rafters varying in size from 2X4 to larger members (nominal cross section dimension) and lengths from 8-ft to 16-ft will be

tested individually to failure by applying a vertical load. Individual rafters (figure 2) and rafter systems (figure 3) will both be tested.

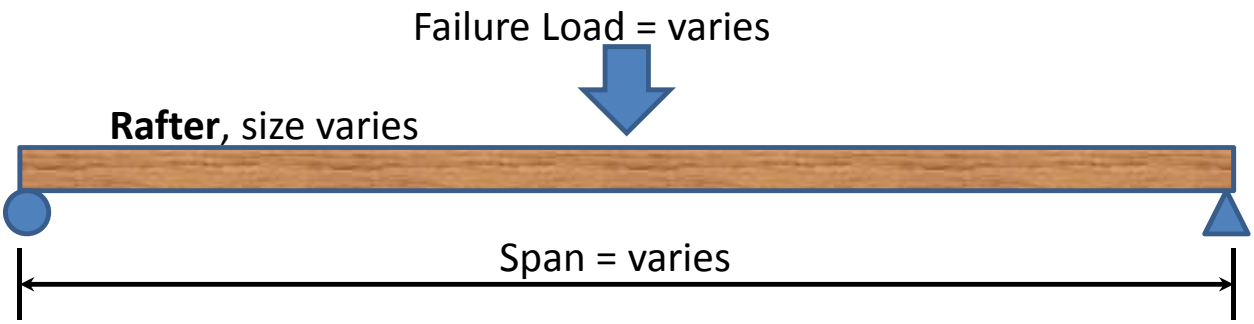

Figure 2. Point Load on Single Member Test Configuration

Each respective rafter tested individually will also be tested for composite action to failure similar to that shown in Figure 4. A minimum of three rafters spaced at 2-ft on center will be placed in parallel and attached to typical OSB sheathing. The point load will be applied directly above the middle rafter.

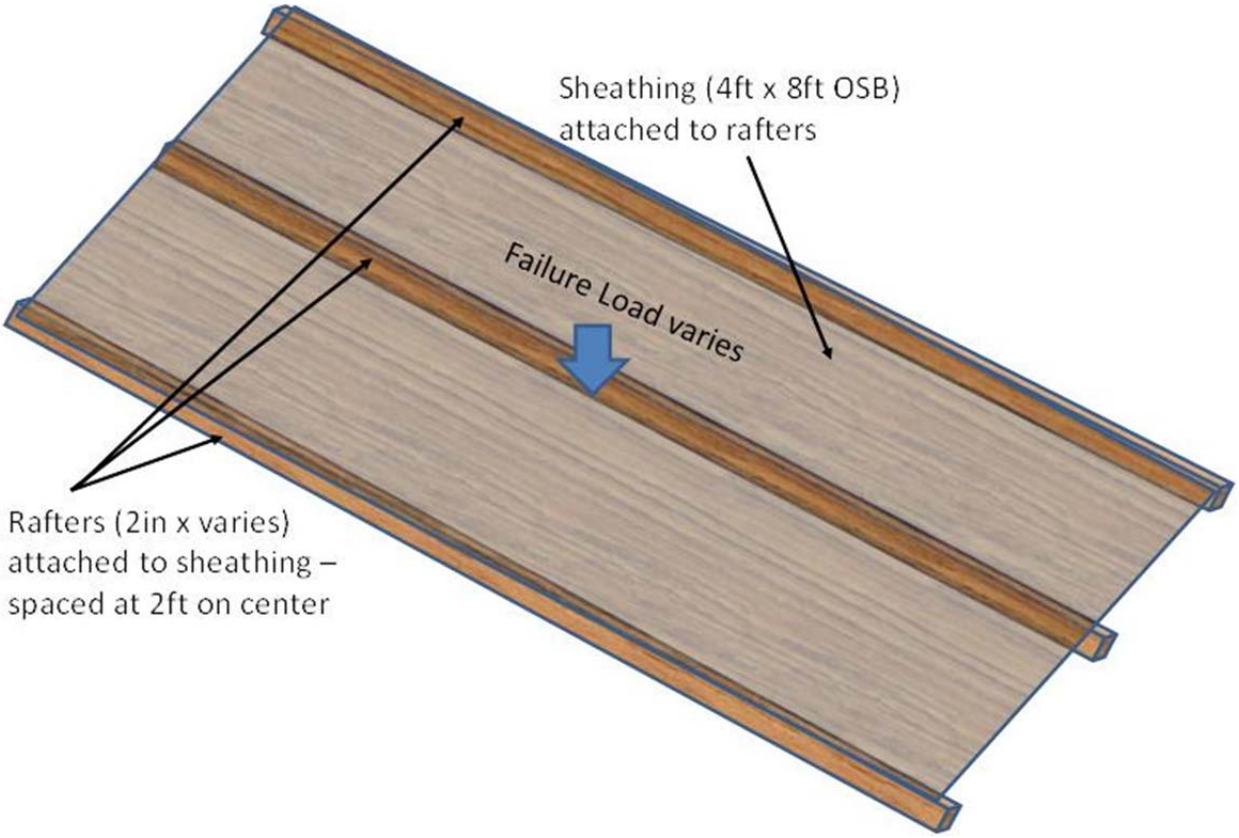

Figure 3. Point Load on Composite Test Assembly

Subsequent tests will include uniform load application that better mimics actual live roof loads such as wind and snow. Pressure will be evenly distributed across the entire surface of the rafter/joist or OSB sheathing depending on the test configuration. The pressure will be recorded at failure to determine the load bearing capacity of the member or system tested.

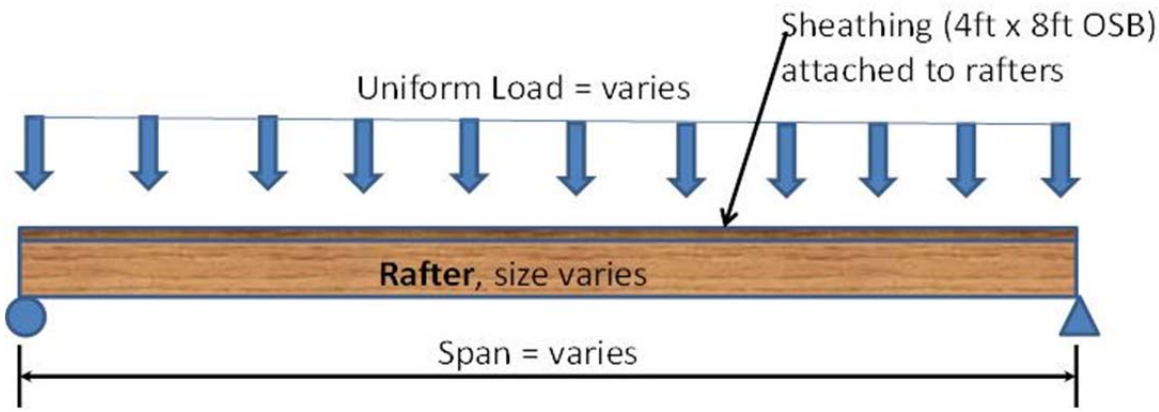

Figure 4. Uniform Load Applied on Test Configuration

b. Trusses

Trusses will be tested upon completion of rafter testing. Space trusses will be tested to failure similar to that shown in figures 2 to 4. Multiple size and shapes of trusses will be tested individually. Each respective truss tested individually will also be tested in composite action similar to figures 5 and 6.

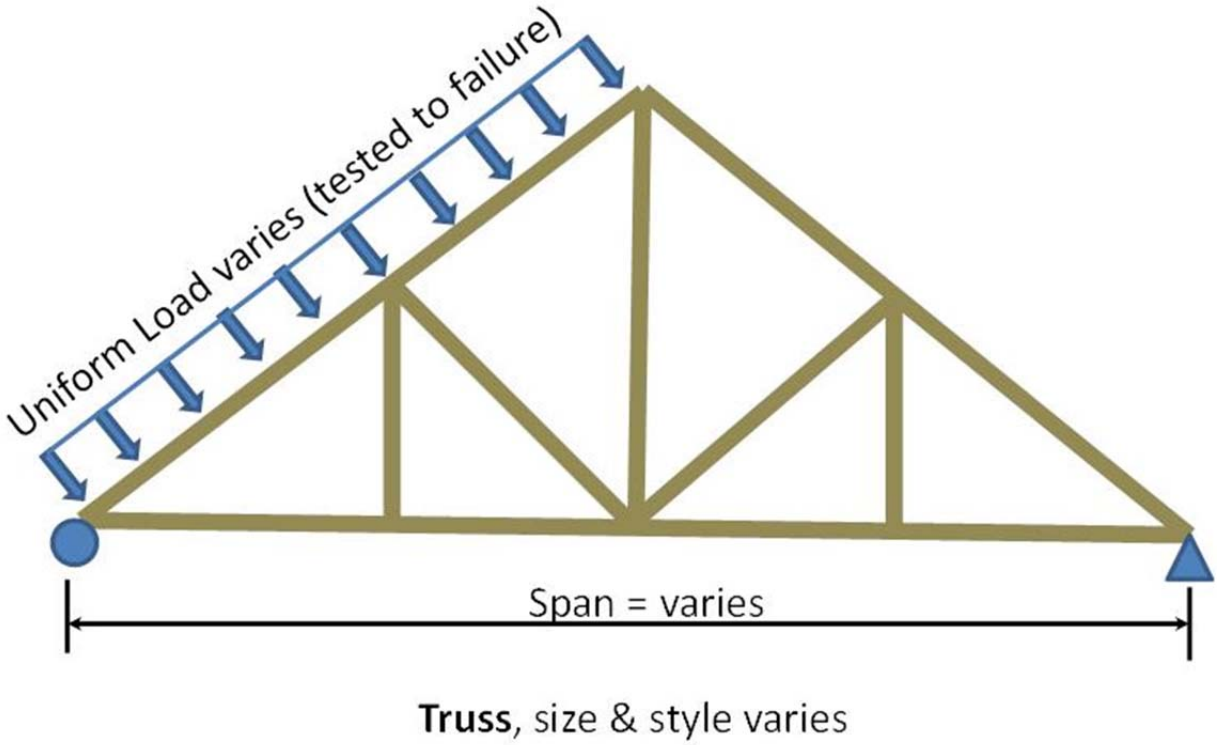

Figure 5. Uniform Load Applied to Space Truss

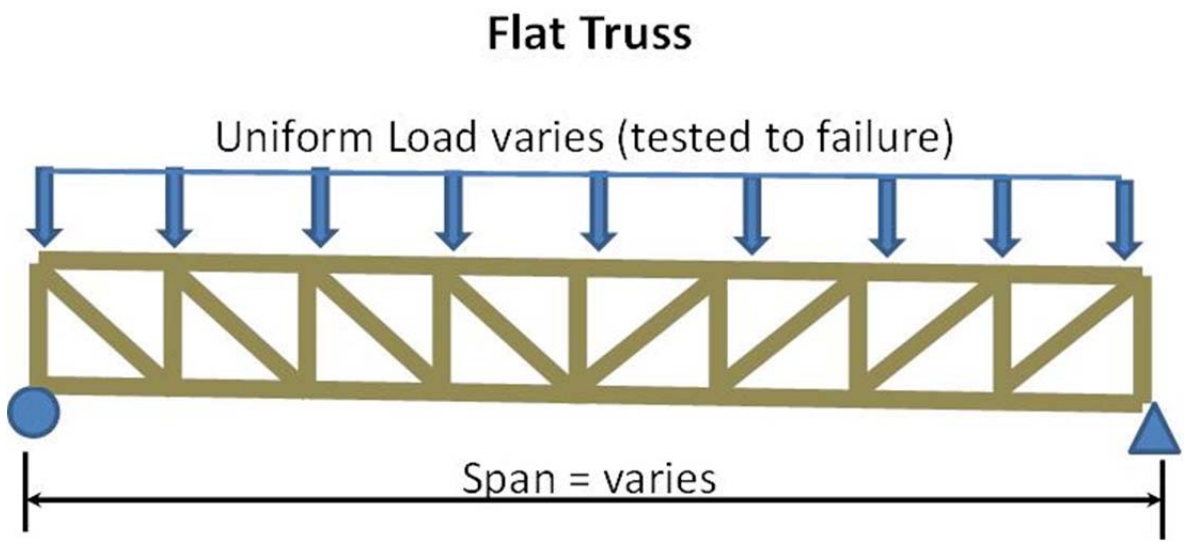

Figure 6. Uniform Load Applied to Flat Space Truss

9. Test Results

All tests will be recorded and documented. It is anticipated that a minimum of three similar tests will be conducted to allow for statistical validation of results. The results will be formalized in reports and submitted to the designated DOE SunShot representative.

The results will contain the following minimum information:

Table 2. Point Test Results

Test	Member		Failure Load		Actual Load Bearing Capacity (Tested)	Code Load Bearing Capacity (Calculated)	Difference (Actual less Code)	Failure Description
	Size	Length	Point Load	Uniform Load				

Table 3. Uniform Load Test Results

Test	Test Configuration					Failure Load		Actual Load Bearing Capacity (Tested)	Code Load Bearing Capacity (Calculated)	Difference (Actual less Code)	Failure Description
	Size	Length	Number of Rafters/Trusses	Spacing of members	Sheathing Surface Area (Load application surface area)	Point Load	Uniform Load				

10. Environmental, Safety, and Health (ES&H) Requirements

ES&H requirements set forth by Sandia National Laboratories have been employed in addition to those in place at the University of New Mexico. A primary hazard screening (PHS) was completed (PHS Number: SNL13A00079-001). This screening process ensured the analysis and assessment of all risks associated with the work to be performed and compliance with all applicable ES&H and legal controls in place governing the safe completion of all work. It also allows for an assessment of quality considerations of the tasks to be completed.

A NEPA permit was also applied for (NEPA ID: NM13-0200). This permit process included completion of a NEPA checklist that assesses all ES&H concerns, environmental regulations, requirements, and quality standards.

11. References

1. ASCE 7-10 (2010). Minimum Design Loads for Buildings and Other Structures. American Society of Civil Engineers, Structural Engineers Institute.
2. IBC 2009. International Building Code. International Code Council.
3. IRC 2009. International Residential Code. International Code Council.
4. SAND2013-2090 (2013). Literature Review: Reducing Soft Costs of Rooftop Solar Installations Attributed to Structural Considerations. Sandia Report.
5. National Design Specification for Wood Construction (2012). American Wood Council.

Distribution

1	MS0706	Stephen F. Dwyer	6912 (electronic copy)
1	MS0899	Technical Library	9536 (electronic copy)

Sandia National Laboratories