TriTruss Strut-to-Joint Bond Test: Analysis and Setup

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The TriTruss is a novel structural module developed by researchers at NASA Langley Research Center (LaRC) that can be used in space to assemble large backing structures for a variety of applications. One such application is the metering truss or primary mirror backbone support structure of an in-space assembled telescope (iSAT). For the iSAT application, the TriTruss will be supporting mirror segments, payloads, and instruments, all of which require the TriTruss to have robust structural integrity. Structural proof tests are needed to ensure the integrity of the bonded interface between the joint and struts that make up a TriTruss module. For the first phase of the analysis and test setup effort, described in this paper, a series of analyses were performed to determine the optimal test setup for applying a single set of loads to a module to verify the integrity of the bonds. This paper describes the test setup configurations and loads considered and summarizes the final set of loading states that were selected for proof testing each module.

Nomenclature

a	=	Length of face triangle strut
H	=	TriTruss module depth
L_b	=	Length of batten member
L_c	=	Length of central triangle strut
d_s	=	Diameter of strut

I. Introduction

SPACE operations are on the cusp of a revolutionary new operational paradigm that leverages modular systems and repeated robotic visits to "Persistent Assets", enabling asset maintenance, repair, and enhancement. A "Persistent Asset" (PA) is defined here as any near zero-gravity (zero-g) or planetary surface system that benefits from multiple visits [1]. These visits can be used for assembly, servicing, repairs, reconfiguration, and upgrades [2–6]. A key attribute to include when developing such systems is to design them to be modular. The efficiency and robustness of on-orbit assembly operations can be maximized by co-designing modular structures, such as the TriTruss, and their associated connectors for robotic handling and joining. One example of a PA that is currently being considered is the In-Space Assembled Telescope (iSAT) shown in Fig. 1.

A study was conducted in 2019 [7, 8] that determined the feasibility of designing a large space telescope, the iSAT, and concluded that in order to achieve large apertures (>15-meter diameter primary aperture), robotic in-space assembly of modular components was necessary. The study also concluded that the foundational structure for the telescope, consisting of the metering truss and the primary mirror support truss, should be assembled from modular truss elements that could be packaged prior to launch, deployed on-orbit, and robotically assembled into the final configuration. The truss structure is illustrated in Fig. 2a. Although a specific truss design was not selected during the study, the iSAT structures team baselined the modular TriTruss system for the telescope foundational structure [9].

The TriTruss [10] was developed by researchers at NASA Langley Research Center (LaRC) for systems with triangular or hexagonal topologies, flat or curved, such as telescopes and other platforms (see Fig. 2b). The TriTruss has equilateral triangular faces at the top, bottom, and middle. The top triangular face is smaller than the bottom face of the truss when used to support curved surfaces such as telescope primary mirror support structures. The TriTruss has many innovative attributes including design versatility, compact packaging abilities, robotically actuated deployment, and

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multiple locations for payload attachment. The TriTruss concept was first introduced in Ref. [10] where the details of its design parameters and structural configuration were described.

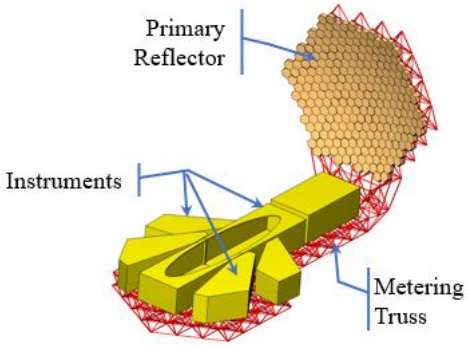
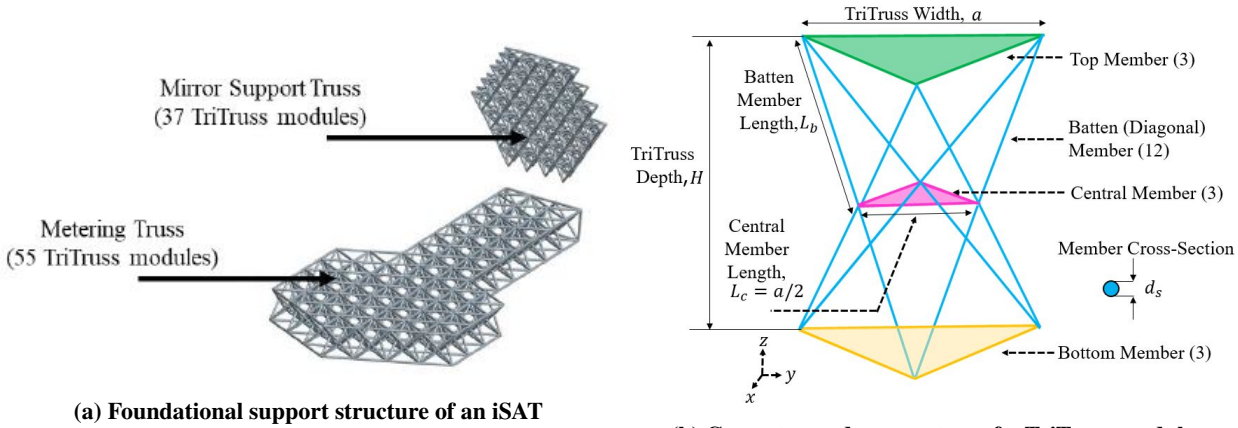


Fig. 1 Large in-space assembled telescope [10].



(a) Foundational support structure of an iSAT

(b) Geometry and parameters of a TriTruss module

Fig. 2 The foundational truss structure of an iSAT assembled from individual TriTruss modules.

In Ref. [10], many different mission applications for the TriTruss are discussed, including a 20-meter diameter space telescope and a beam-type platform that can be used to host payloads and instruments. The geometry and various design variables for the TriTruss are also described. The TriTruss module geometry consists of top- and bottom-face equilateral triangles (strut length, a) with an equilateral central triangle (strut length, $a/2$) located halfway between the two faces. Core struts with length L_b (that depend on truss depth, H) connect the central triangle with the face triangles [9].

Bonded joints will be used to connect struts to corner fittings to form the TriTruss. Subjecting the TriTruss modules to proof loading is essential to validate the structural integrity of the bonds. This paper describes the analysis performed to define an optimum test procedure, as well as plans for test execution.

II. Analysis Overview

Finite element analysis was performed using commercially available Abaqus software.* Finite element models of a single TriTruss module were developed and analyzed to determine the loading states that will be used for the testing. Joint properties were not considered for this analysis since the only desired information is the loads in the individual TriTruss struts. Only beam elements were included in the model to represent the struts which were assumed to be perfectly connected at the joints. Two different orientations of the TriTruss, with several different loading states applied to each orientation, were analyzed. The objective of the test is to apply 2000 N tension or 1000 N compression loading to each bonded joint.

*Information available online at https://www.3ds.com/products-services/simulia/products/abaqus/ [accessed May 2021]

A. Top Suspension Configuration

In the first orientation analyzed, called the Top Suspension Configuration, the TriTruss is considered in the upright position (see Fig. 2b) and masses are applied at various locations to different parts of the TriTruss. Initially, a total of ten loading states were analyzed for the Top Suspension Configuration. For five of those states, masses would hang directly from the TriTruss joints which were modeled as point loads applied at the joint locations where mass would be attached. These loading states are illustrated in Fig. 3. For the other five loading states, cable ends were attached to adjacent joints and the masses suspended from a single location on the cables which were modeled as truss elements. These loading states are shown in Fig. 4. For all loading states, a constant total mass of 200 kg was applied for the initial analyses. Including the mass of a single TriTruss module, estimated to be 7.4 kg, the total applied mass to the suspension system is 207.4 kg. For the analysis, the mass of the cables was neglected. The corresponding total force was divided equally among the load application locations as appropriate for the different configurations analyzed as shown in Fig. 3. For the loading states that involved cables, as shown in Fig. 4, the total force was applied to a single location as represented by the circle connecting the lines. The applied force location was varied for each of the cable arrangements by adjusting the three cable lengths in the analysis ($L1$,$L2$,$L3$) to change the resulting strut loading distribution.

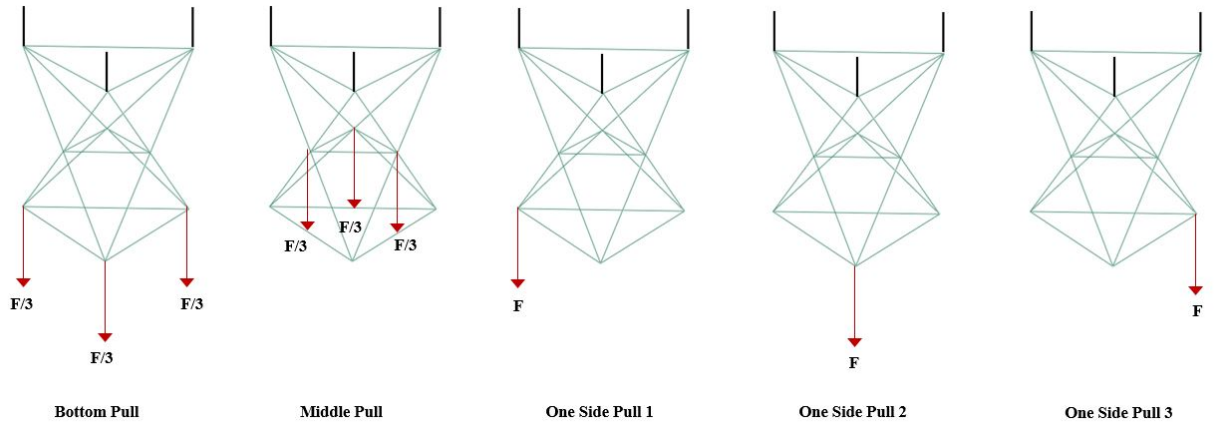


Fig. 3 Top Suspension loading states without cables.

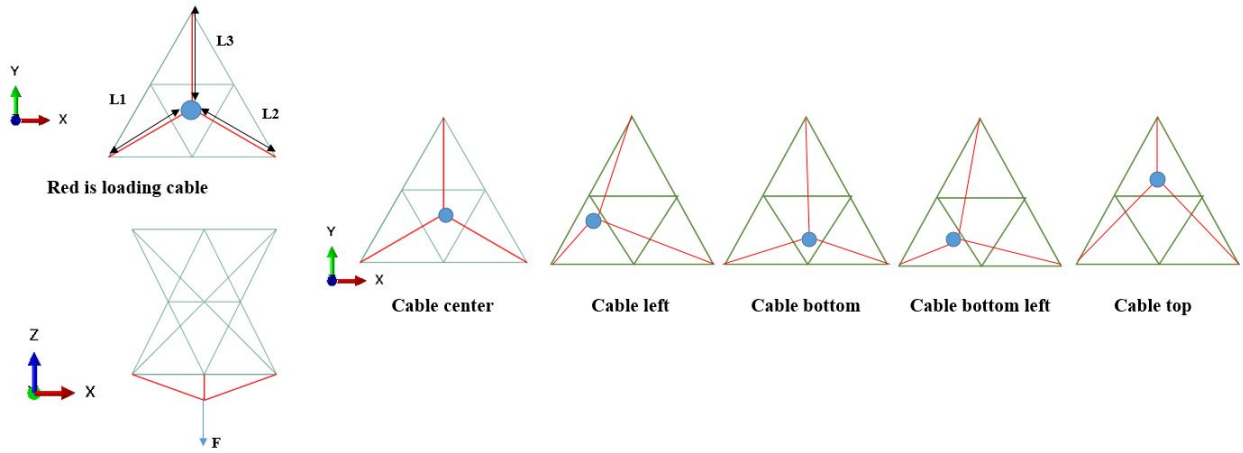


Fig. 4 Top Suspension loading states with cables.

B. Side Suspension Configuration

In the second orientation analyzed, considered the Side Suspension Configuration, masses are applied at joint locations on the vertical side of the TriTruss module. There were a total of eight loading states analyzed in this

orientation. For five of those states, hanging mass directly from the TriTruss joints were modeled as point loads at the joint, as shown in Fig. 5. The other three loading states analyzed had a single mass suspended from multiple cables, as shown in Fig. 6. As in the previous analysis, a total mass of 207.4 kg was applied to the TriTruss module. The corresponding total force was divided equally among the load application locations as appropriate for the different states analyzed without cables. For the loading states with cable attachments shown in Fig. 6, the force was applied at a single location, represented by the circle connecting the lines from the suspended TriTruss.

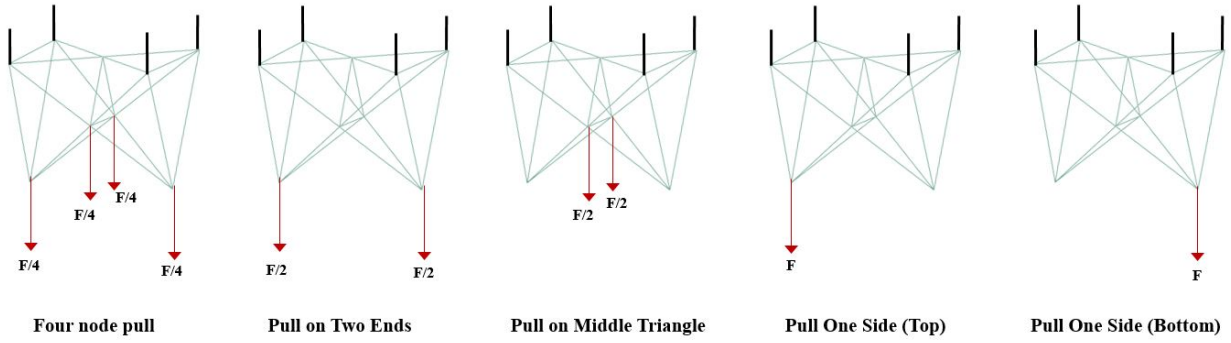


Fig. 5 Side Suspension loading states without cables.

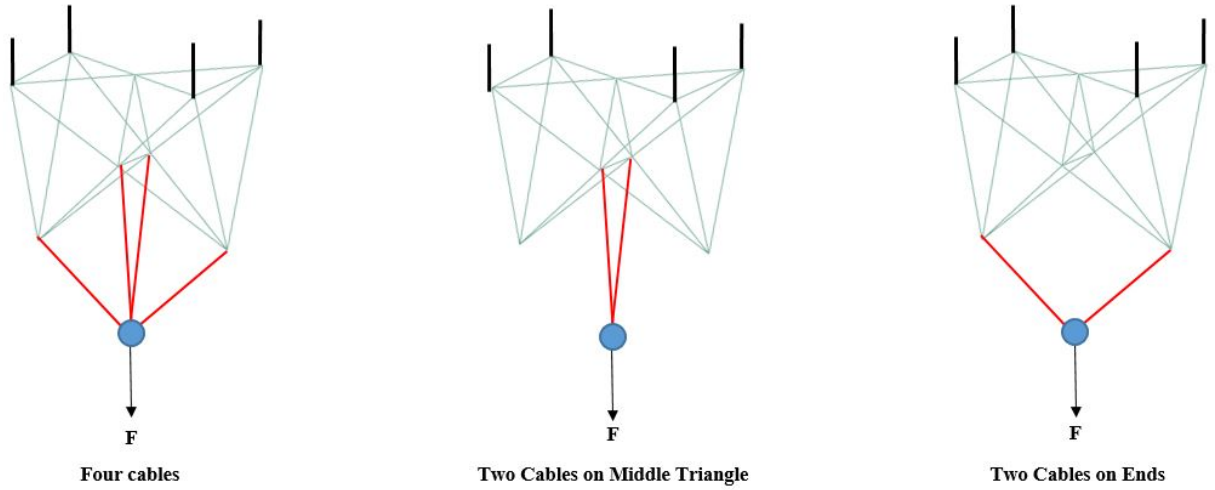


Fig. 6 Side Suspension loading states with cables.

III. Results and Discussion

Finite element analyses were performed to determine the 21 TriTruss member loads for each of the loading states and configurations described above. In order to ease tracking, each of the TriTruss struts was assigned an identifier to which the internal load was mapped, as shown in Fig. 7. The struts that make up the top triangle are noted as Top1, Top2, and Top3. A similar designation is used for the middle triangle and the bottom triangle in the TriTruss. The diagonal struts in the top half of the TriTruss are labeled "DT" and the diagonal struts at the bottom half are labeled "DB". A numbering system is then assigned to each of these diagonal struts. The internal resultant forces for each of these struts subjected to all of the different loading states described above are summarized in Table 1 for the Top Suspension Cases and Table 2 for the Side Suspension Cases.

In the tables, the largest forces shown for each loading condition are displayed in bold font. The red text indicates the largest tension forces while the blue text indicates the largest compressive forces. In all these cases, the total applied mass was kept constant and changes in the loading distribution were compiled with the goal of achieving the target

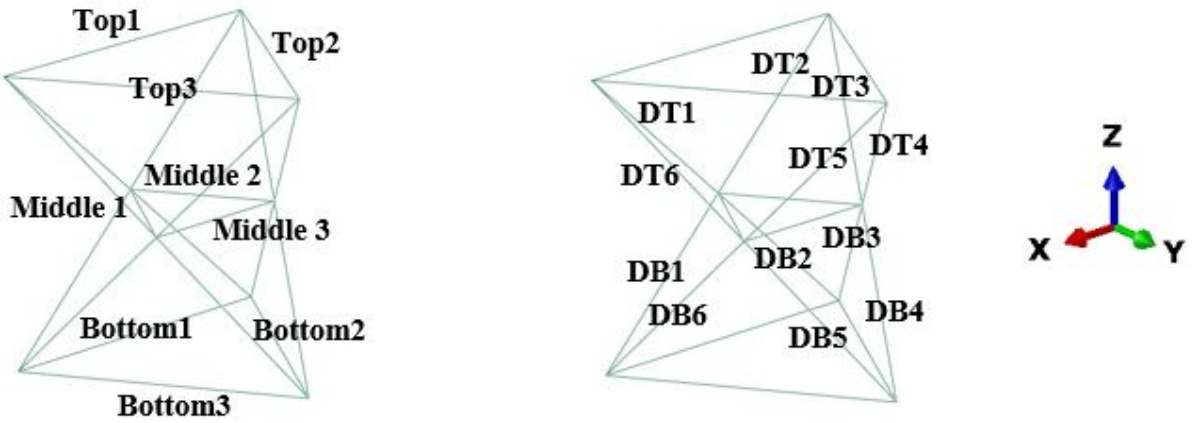


Fig. 7 Nomenclature used for strut numbering.

Table 1 Summary of loads for Top Suspension Cases, in Newtons (N).

	With Cables					Without Cables				
	Cable center	Cable left	Cable bottom	Cable bottom left	Cable top	Bottom Pull	Middle Pull	One Side Pull 1	One Side Pull 2	One Side Pull 3
Top1	-338	-338	-675	-675	-0.8	-338	-338	-1012	-1012	1011
Top2	-338	-843	-169	-675	-506	-338	-338	1011	-1012	-1012
Top3	-338	168	-169	336	-506	-338	-338	-1012	1011	-1012
Middle1	-0.06	1.35	-0.52	0.79	0.38	0.02	0.012	-3.03	1.56	1.55
Middle2	-0.06	-1.34	-0.52	-1.7	0.38	0.02	0.012	1.56	-3.03	1.55
Middle3	-0.06	-0.15	0.88	0.79	-0.92	0.02	0.012	1.55	1.55	-3.03
Bottom1	-1600	-890	-2646	-1937	-711	-338	0.0029	-1012	-1012	1011
Bottom2	-1600	-3051	-958	-1937	-1926	-338	0.0018	1011	-1012	-1012
Bottom3	-1600	-148	-958	21	-1926	-338	0.0018	-1012	1011	-1012
DT1	478	477	955	954	1.26	478	478	1433	1430	-1429
DT2	478	479	955	956	1.26	478	478	1430	1433	-1429
DT3	478	1193	240	956	716	478	478	-1429	1433	1430
DT4	478	1193	239	954	717	478	478	-1429	1430	1433
DT5	478	-237	239	-476	717	478	478	1430	-1429	1433
DT6	478	-238	240	-476	716	478	478	1433	-1429	1430
DB1	478	477	954	953	1.28	478	-0.0008	1433	1430	-1429
DB2	478	479	954	955	1.28	478	-0.0008	1430	1433	-1429
DB3	478	1193	240	955	716	478	0.0013	-1429	1433	1430
DB4	478	1192	239	954	717	478	0.0006	-1429	1430	1433
DB5	478	-236	239	-475	717	478	0.0006	1430	-1429	1433
DB6	478	-238	240	-475	716	478	0.0013	1433	-1429	1430

internal tension (2000 N) or compression (-1000 N) load for each strut. The 2000 N target load was selected due to the struts having a tensile failure at approximately 4000 N from previous testing of a single strut and similarly, the -1000 N target load was selected based on previous testing where a single strut experienced a buckling failure at approximately -2000 N. The target loads were selected to be approximately half the value of the measured strut failure loads to avoid failure in the struts during testing. The structural integrity of the bonded joints can then be assessed up to the target loads.

For the Top Suspension Configuration without cables, the middle pull state was eliminated from consideration because it did not induce significant forces in many of the struts. All of the one side pull cases were eliminated due to the large compressive forces that were induced in many of the struts. Although reducing the applied mass to achieve the 1000 N compression goal is an option, this would have the negative consequence of lowering the tensile force induced in many of the struts from the 2000 N targeted value. The bottom pull condition achieved a desirable internal loading distribution, with evenly distributed forces among all of the struts. All of the Top Suspension orientations with cables were eliminated from consideration due to uneven loading distributions, insignificant loading, or excessive

Table 2 Summary of loads for Side Suspension Cases, in Newtons (N).

	With Cables			Without Cables				
	Four Cables	Two Cables on Ends	Two Cables on Middle Triangle	Four Node Pull	Pull on Two Ends	Pull on Middle Triangle	Pull One Side (Top)	Pull One Side (Bottom)
Top1	-63.7	-1523	291	-0.54	-292	291	-585	0.19
Top2	356	1817	0.72	293	585	0.74	1171	-0.1
Top3	356	1817	0.72	293	585	0.74	1171	-0.1
Middle1	0.37	-1.97	0.94	0.49	-0.08	1.07	-0.08	-0.08
Middle2	0.37	-1.97	0.94	0.49	-0.08	1.07	-0.08	-0.08
Middle3	151	3.98	187	292	0.29	583	0.29	0.29
Bottom1	-63.7	-1523	291	-0.54	-292	291	0.19	-585
Bottom2	356	1817	0.72	293	585	0.74	-0.1	1171
Bottom3	356	1817	0.72	293	585	0.74	-0.1	1171
DT1	-324	1739	-826	-413	-0.5	-826	-0.7	-0.31
DT2	-324	1739	-826	-413	-0.5	-826	-0.7	-0.31
DT3	324	-1740	826	413	0.47	826	0.7	0.25
DT4	-342	-1744	-0.24	-0.03	0.16	-0.22	0.25	0.06
DT5	-342	-1744	-0.24	-0.03	0.16	-0.22	0.25	0.06
DT6	324	-1740	826	413	0.47	826	0.7	0.25
DB1	-324	1739	-826	-413	-0.5	-826	-0.31	-0.7
DB2	-324	1739	-826	-413	-0.5	-826	-0.31	-0.7
DB3	324	-1740	826	413	0.47	826	0.25	0.7
DB4	-342	-1744	-0.24	-0.03	0.16	-0.22	0.06	0.25
DB5	-342	-1744	-0.24	-0.03	0.16	-0.22	0.06	0.25
DB6	324	-1740	826	413	0.47	826	0.25	0.7

compressive forces in each of the struts. As a result, the bottom pull without cables condition was judged to be the best option for the Top Suspension Configuration. Evaluation of the results for the Side Suspension without cables reveal that either insignificant loading or an uneven loading distribution occurred for all the cases analyzed. For the loading states involving four cables or those having two cables on the middle triangle, there was still insignificant internal loads in several struts. The support condition having two cables on the ends was judged to be the best option for the Side Suspension Configuration since it resulted in the least number of unloaded struts (Middle1, 2, and 3).

After selecting the best Top and Side Suspension cases based on the preliminary analyses, a more in-depth study was initiated for these two options. The bottom pull case displayed a desirable loading distribution where all of the TriTruss diagonal struts experienced the same tension force and the top and bottom triangles experienced the same compressive force and thus, the bottom pull condition was selected for testing purposes. However, since this load case did not result in the desired internal load values of 2000 N or -1000 N, the analyses were conducted varying the applied mass to determine what mass is required so that all struts achieve the optimal internal load. For all the load cases analyzed, insufficient load was observed in the struts making up the middle triangle. Data summarized in Table 1 and Table 2 show that the induced loads in the middle triangle were either insignificant or were not evenly distributed among the middle triangle struts. In order to induce sufficient and equal loads in the middle triangle, a configuration where cables are attached to the middle triangle and a mass hung from a central location (that connects to each of the cables on the triangle) was investigated. Results for these cases are included in Table 3.

A total of four new support cases are highlighted in yellow in Table 3 for the Top Suspension loading states. In three of these cases, cables were added to the middle triangle with attached 200 kg mass. While maintaining 200 kg of applied mass, the first variable studied was the distance the mass was applied below the middle triangle. Placing the mass 0.3 m below the triangle resulted in a compressive force that was too large while placing it at 0.5 m below the triangle resulted in a compressive force that was too small. In the final case analyzed, the mass was placed at a distance of 0.5 m below the middle triangle but was increased to 300 kg. This combination produced the desired approximate magnitude of internal forces in the central triangle struts of the TriTruss and was selected as one of the configurations that will be used for TriTruss proof testing. Although the 0.3 m case with a lighter mass would also produce the desired internal forces in the strut, the 0.5 m case provides more clearance below the middle triangle which is desired for testing purposes

As mentioned previously, the bottom pull arrangement option also has the potential to give good test results, although additional mass would be needed to achieve the desired internal loads. By increasing the applied mass from 200 kg to 600 kg in this configuration, the desired internal loads are achieved in all of the struts except those in the middle triangle. By combining the bottom pull that includes the increased mass condition with cables attached to the middle triangle with a larger mass 0.5 m below the triangle, all of the struts in the TriTruss module achieve close to the desired internal

Table 3 Summary of loads for Top Suspension Cases, in Newtons (N).

	Cables on Bottom Triangle					Cables on Middle Triangle			Without Cables					
	Cable center	Cable left	Cable bottom	Cable bottom left	Cable top	0.5 m below triangle	0.3 m below triangle	Mass Increase, 0.5 m below triangle	Bottom Pull	Bottom Pull-Mass Increase	Middle Pull	One Side Pull 1	One Side Pull 2	One Side Pull 3
Top1	-338	-338	-675	-675	-0.8	-338	-338	-501	-338	-989	-338	-1012	-1012	1011
Top2	-338	-843	-169	-675	-506	-338	-338	-501	-338	-989	-338	1011	-1012	-1012
Top3	-338	168	-169	336	-506	-338	-338	-501	-338	-989	-338	-1012	1011	-1012
Middle1	-0.06	1.35	-0.52	0.79	0.38	-631	-1052	-935	0.02	0.072	0.012	-3.03	1.56	1.55
Middle2	-0.06	-1.34	-0.52	-1.7	0.38	-631	-1052	-935	0.02	0.072	0.012	1.56	-3.03	1.55
Middle3	-0.06	-0.15	0.88	0.79	-0.92	-631	-1052	-935	0.02	0.072	0.012	1.55	1.55	-3.03
Bottom1	-1600	-890	-2646	-1937	-711	-0.019	-0.033	-0.028	-338	-989	0.0029	-1012	-1012	1011
Bottom2	-1600	-3051	-958	-1937	-1926	-0.02	-0.034	-0.029	-338	-989	0.0018	1011	-1012	-1012
Bottom3	-1600	-148	-958	21	-1926	-0.02	-0.034	-0.029	-338	-989	0.0018	-1012	1011	-1012
DT1	478	477	955	954	1.26	478	478	708	478	1400	478	1433	1430	-1429
DT2	478	479	955	956	1.26	478	478	708	478	1400	478	1430	1433	-1429
DT3	478	1193	240	956	716	478	478	708	478	1400	478	-1429	1433	1430
DT4	478	1193	239	954	717	478	478	708	478	1400	478	-1429	1430	1433
DT5	478	-237	239	-476	717	478	478	708	478	1400	478	1430	-1429	1433
DT6	478	-238	240	-476	716	478	478	708	478	1400	478	1433	-1429	1430
DB1	478	477	954	953	1.28	-0.017	-0.028	-0.026	478	1400	-0.0008	1433	1430	-1429
DB2	478	479	954	955	1.28	-0.017	-0.028	-0.026	478	1400	-0.0008	1430	1433	-1429
DB3	478	1193	240	955	716	-0.015	-0.026	-0.023	478	1400	0.0013	-1429	1433	1430
DB4	478	1192	239	954	717	-0.016	-0.027	-0.024	478	1400	0.0006	-1429	1430	1433
DB5	478	-236	239	-475	717	-0.016	-0.027	-0.024	478	1400	0.0006	1430	-1429	1433
DB6	478	-238	240	-475	716	-0.015	-0.026	-0.023	478	1400	0.0013	1433	-1429	1430

load without risking failure in other struts. Thus these two loading states will be used in the proof test by applying each loading state separately to the TriTruss module. Another advantage to using these two cases is that they are both in the Top Suspension configuration so rigging the TriTruss for testing only require changes in the mass connections, compared to using a combination of loading configurations which would also require overhead rigging changes.

IV. TriTruss Bonded Joint Test Setup

The objective of the TriTruss bonded-joint test is to load all the bonded joints in each TriTruss module and verify structural integrity. The approach chosen to accomplish the loading is to add masses to the TriTruss joints in different arrangements and then lift the TriTruss module to allow the masses to apply load to the bonds at all the joints. The objective of the analysis is to study a variety of possible lifting configurations and find the minimum number of configurations necessary that will produce either an approximately 2000 N tension force or 1000 N compression force in all 21 struts of the TriTruss module. The same type of struts will be used in the assembled TriTruss modules, each of which will undergo proof testing. In order to avoid strut failure, no strut will be subject to more than 2000 N tension force or 1000 N compression, but either applied load is sufficient to validate the joint.

A proposed setup for the test includes 3 sets of slings and shackles connecting the triangular spreader bar to the hook and then 3 more sets of shackles and vertical slings connecting the triangular spreader to a steel bracket installed on the TriTruss top corner nodes as shown in Fig. 8. The masses used to apply loading to the TriTruss module will be suspended from the bottom of the TriTruss module using additional slings attached to the same steel bracket attached to the bottom corner nodes. An overhead crane will be used to lift the assembly off the ground, thus initiating the loading of the TriTruss module. An illustration of this setup is shown in Fig. 8. The masses will be suspended on the TriTruss by fabricating a custom made hangar. The mass hanger will consist of a steel rod with a custom made plate at the bottom, where all the masses will be stacked, and an eye nut will be installed at the top of the rod as depicted in Fig. 9. The slings from the TriTruss corners will attach to the eye nut suspending the mass hanger from the module when the TriTruss is lifted.

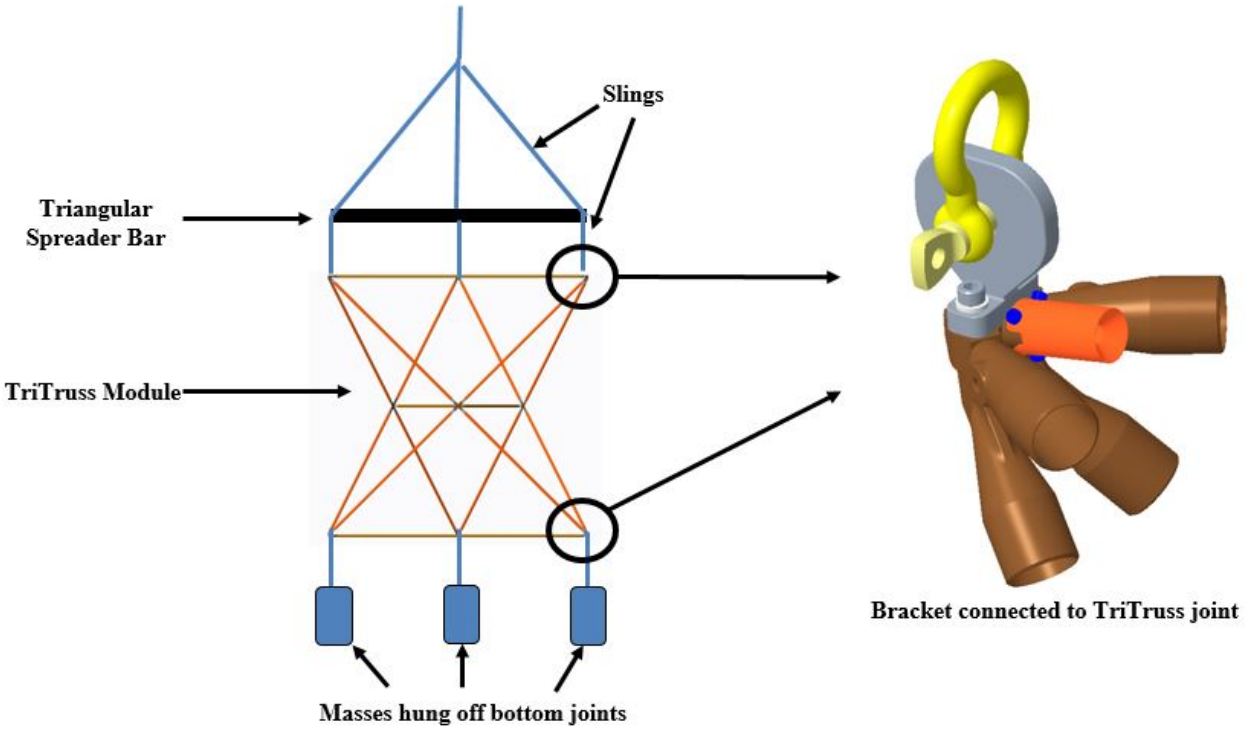


Fig. 8 TriTruss bond test setup.

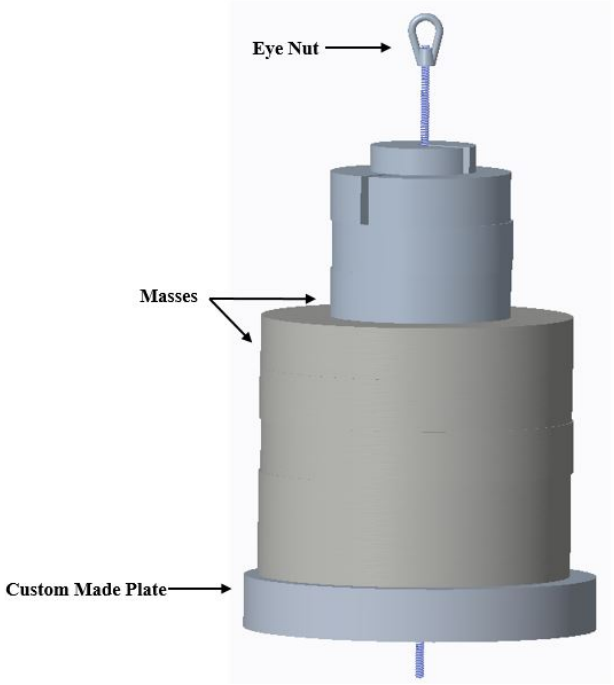


Fig. 9 Mass hanger with masses.

V. Concluding Remarks

This paper has described the objectives and approach for performing the TriTruss bond joint proof test. Analyses were performed to determine the TriTruss test configuration and applied loading states that would result in the TriTruss

strut loads achieving predetermined target values of either 2000 N in tension or 1000 N in compression. Two individual tests will be carried out for each loading state that, together, result in all of the struts achieving their target loads. In the next phase of this work, TriTruss modules will be fabricated, instrumented, and proof tested to verify the structural integrity of the bonded joints up to the target loads.

Acknowledgments

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