2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC

Host Sponsor UNC Charlotte

Paper ID #51035

A Low-Cost Spanned Anchor Simulator for Firefighter Training and Statics Education Developed Via University–Fire Department Collaboration

Jake Joseph Ormanic, University of Florida - GatorKits Laboratory

My name is Jake Ormanic, and I'm a Mechanical Engineering student at the University of Florida. My academic interests consist of manufacturing, applied mechanics, and robotics. I contributed to this paper as an author through research, design, and analysis related to firefighter training and statics education.

Ernest Richard Wright
Dr. Matthew J. Traum, University of Florida

Dr. Matthew J. Traum is a Master Lecturer and Instructional Full Professor in the Department of Mechanical & Aerospace Engineering at the University of Florida (UF) where he leads GatorKits Laboratory as PI. He is a Fellow of Sigma Xi, the International Scientific Research Honor Society, and he is an elected Sigma Xi Director representing the Southeast Region. Dr. Traum is an experienced educator, administrator, fundraiser, and researcher. As of 2026, he has co-authored 1 book chapter, published 90 refereed journal and conference papers, written an engineering design Open Educational Resource (OER) textbook, and attracted over $1.43 Million in funding as PI or Co-PI. Prior to UF, Dr. Traum was founding CEO of Engineer Inc., a successful education technology social enterprise and pioneer in STEM instructional lab kits for remote learning.

Previously, Dr. Traum was an Associate Professor and Director of Engineering Programs at Philadelphia University. He also served on the Milwaukee School of Engineering faculty as well as co-founding the Mechanical & Energy Engineering Department at the University of North Texas – Denton.

Traum received Ph.D. and M.S. degrees in mechanical engineering from MIT, and he holds two B.S. degrees from the UC Irvine in mechanical engineering and aerospace engineering.

A Low-Cost Spanned Anchor Simulator for Firefighter Training and Statics Education Developed Via University–Fire Department Collaboration

Abstract

Spanned anchors are ropes attached between fixed points to create a descent zone when natural anchors are unavailable along an over-ledge line of descent. As span horizontal included angle increases, anchor forces can significantly exceed the applied load. This counterintuitive effect is not fully addressed in firefighter manuals, which rely on tabulated angle multipliers and assume centered symmetrical loading.

Gainesville Fire Rescue (GFR) partnered with the University of Florida's Mechanical & Aerospace Engineering (MAE) Department to analyze forces induced by spanned anchor rope systems used during their advanced over-ledge rescues. The collaborative objective was improving firefighters' intuitive understanding of statics-based force amplification in spanned anchors. This study was guided by two research questions:

(1) How accurately do tabled spanned anchor guidelines available to firefighters predict anchor point forces under centered loading?

(2) Can a low-cost physical simulator improve conceptual firefighter understanding of force amplification in spanned anchor systems?

An inexpensive tabletop spanned anchor simulator was built from common materials, which allowed firefighters to vary span horizontal included angle and load position while directly measuring anchor reaction forces. Measurements were compared and verified against analytical predictions from Statics and guideline multipliers in firefighter field manuals. Key findings include strong agreement between the spanned anchor simulator experiment, static equilibrium equations, and tabulated multipliers. The simulator also demonstrated force prediction capability under load asymmetry, providing utility beyond tables in firefighter manuals.

This work illustrates how community-engaged engineering can enhance public safety while strengthening conceptual understanding of force balance through accessible, low-cost educational kits suitable for firefighter training and engineering classrooms.

Keywords: University–Community Collaboration, Firefighter Training, Statics Education, Rope Rescue Systems, Low-Cost Laboratory Apparatus

Introduction

In firefighting, a spanned anchor system consists of two mechanical anchors connected by a tensioned line, as shown in Figure 1. Spanned anchors create an anchorable zone for descent when none exist in the environment. From the anchor zone, rescuers attach ropes aligned with the intended over-ledge departure point, which allows them to descend (e.g., down the side of a building) at points where natural anchors are unavailable.

Gainesville Fire Rescue (GFR) uses spanned anchors in urban rescues. A persistent challenge has been understanding and quantifying internal forces within spanned anchors under both training conditions and rescues. Firefighters and supporting consultants try to ensure adequate margins of safety in each component. However, firefighters also deal with a "factor of ignorance": they never know exactly what forces they will encounter in a rescue. So, each component in the spanned anchor system is overdesigned with between 6:1 and 10:1 static component safety factors. It is believed this conservative design approach provides ample safety factor even for dynamic events (typically a fall while crawling over an edge) of 1.5:1 to 2:1 force multipliers on equipment. However, component and system safety thresholds are not fully known. This uncertainty necessitates firefighters carrying more equipment weight than is probably necessary for safe operation. Additional weight induces fatigue and more danger for firefighters. So GFR is interested in theoretically and empirically quantifying forces on spanned anchor components to improve firefighter performance and safety.

GFR contacted the Mechanical & Aerospace Engineering (MAE) Department at the University of Florida (UF) to co-design and co-develop a low-cost physical simulator representing GFR's spanned anchor system used for rescues over the sides of tall buildings. There was need for a visual and tactile aid for firefighters to better understand forces on components in their spanned anchor setup. The simulator could also be deployed as a valuable, application-driven, hands-on instructional tool in engineering undergraduate Statics courses. GFR and UF MAE are interested in maintaining a long-term collaborative relationship to quantitatively and empirically evaluate and address uncertainties in firefighter equipment. A long-term goal is making beneficial improvements to hardware and procedures to improve GFR safety and ability to carry out effective rescues.

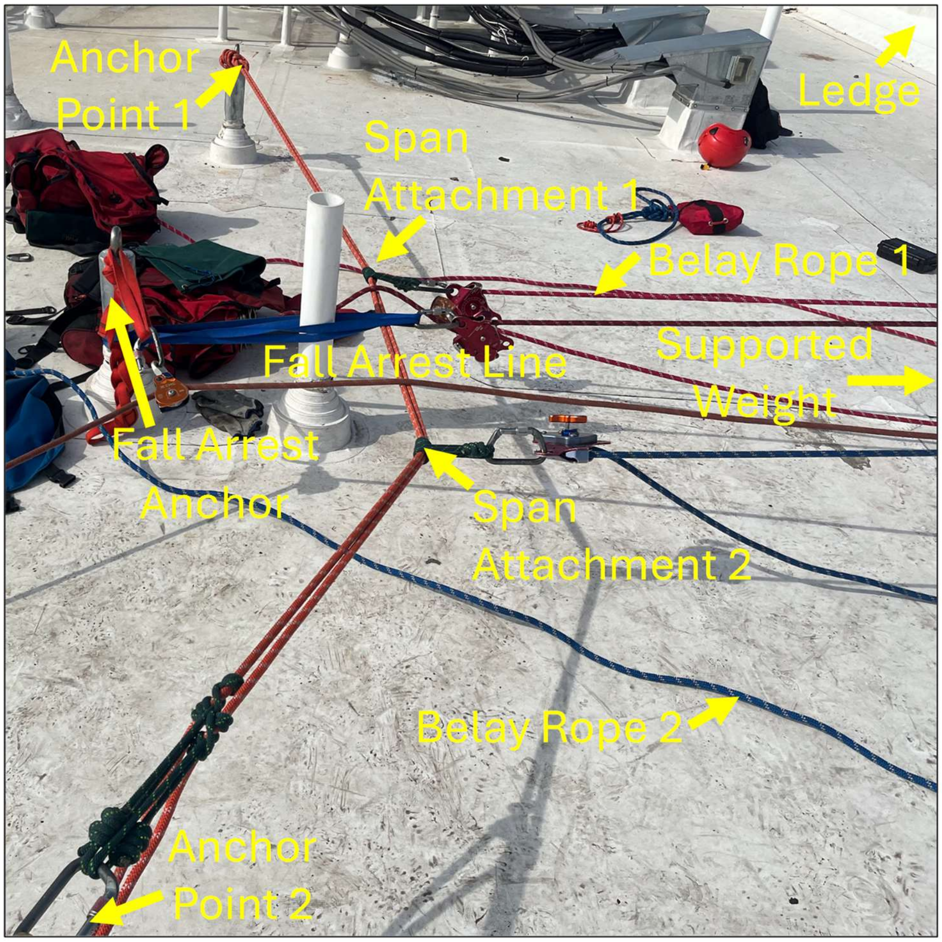

Figure 1: Firefighting spanned anchor setup for over-ledge maneuvers from an urban roof with key elements labeled.

Background

This section reviews relevant scholarship on community-engaged design across engineering education practice, multiple firefighter–university partnership case studies emphasizing co-creation and trust-building, and hands-on instructional research in the pedagogy of engineering Statics. This literature situates the GFR-UF MAE collaboration within established models of reciprocal community partnership, stakeholder integration, and experiential learning.

<u>Community-Engaged Design</u>

This GFR-UF MAE collaboration is an example of Community-Engaged Design, the practice of leveraging community collaboration to create programmatic teaching and research opportunities. A recent instructive case study reported by Oerther was creation of the Caribbean Ocean and Aquaculture Sustainability faciliTy (COAST) [1]. This program integrated engineering, diplomacy, and development finance to address the safety needs of small- and medium-scale fisherfolk in the Caribbean. Framed through Maslow's hierarchy of needs, Oerther argues that engineering designs should move beyond meeting basic physiological needs to co-designing solutions that enhance security, resilience, and long-term sustainability. The result is COAST, a parametric insurance product sold to national governments. It was developed using a three-stage community engagement process: 1) identifying stakeholders and shared problems, 2) collaboratively planning roles and responsibilities, and 3) execution through cycles of action, evaluation, and renewal. The case highlights how community-engaged design and convergence-oriented engineering can generate not only technical artifacts but also sustained collaborations and community resilience.

In another relevant example, Koh describes design and implementation of a two-semester, community-engaged capstone course in response to critical critiques of traditional "Engineering to Help" and service-learning models that often emphasize student learning over community well-being [2]. The course challenged students to define their own community and co-develop project values emphasizing solidarity, non-harm, and long-term impact. Students chose their city as the community of focus and engaged stakeholders through surveys and interviews. They iteratively narrowed their focus to a bicycle safety project to increase driver awareness of cyclists at intersections. This approach revealed tensions between technical progress and sustained stakeholder engagement, as well as gaps in students' preparation for qualitative research and conflict mediation. Koh concludes that community-engaged engineering design requires explicit structures for stakeholder accountability and student familiarity with client jargon to support genuine horizontal university–community partnerships.

Other examples of community-engaged design, in which universities partner with community organizations that generally have non-academic missions to provide pragmatic learning experiences for engineering students appear throughout the literature. Additional examples include university–military partnerships [3], university–agribusiness partnerships [4], and partnerships between universities and residential apartment complexes [5].

<u>University-Fire Department Partnerships</u>

Best practices for university-fire department partnership building, were described by Taylor et al who established and sustain a long-term academic–firefighter collaboration [6]. Throughout this partnership, the firefighters and university researchers were equal partners, co-investigators, and co-contributors in the work. Trust was enabled by a pre-existing relationship: one researcher had worked with firefighters for nearly a decade. Partnership development relied heavily on engaging firefighter leadership who served as key stakeholders, defined priorities, and facilitated access to other firefighters. Iterative in-person engagement in which firefighters reviewed, revised, and validated research instruments were key enablers. These interactions guaranteed research outputs were cast in firefighter-specific language, relevance, and feasibility to ensure understanding and accessibility. The authors emphasize that this partnership-building process fostered mutual learning, community empowerment, and increased awareness, while providing a transferable model for engaging firefighters and academics in research of mutual interest.

Another example of university-fire department partnership was detailed by Walden and Lie who present a case study on development and commercialization of a low-cost cooling vest for rural volunteer firefighters in Australia [7]. These first responders contend with extreme heat stress. Originating from a sports science proof-of-concept, the cooling vest project evolved through a transdisciplinary partnership that included a university design team, a startup responsible for commercializing university-owned intellectual property, and firefighters who were customers and end users. Physical prototyping served as a shared language that aligned scientific, design, useability, and commercial priorities. Firefighters participated actively in the design process with their operational realities shaping every technical and strategic decision. Firefighter protocols also shaped the product's logistics, hygiene considerations, and reliability requirements, reinforcing the need for simplicity and robustness in hazardous conditions.

Delisle et al describe the formation and operation of a partnership between firefighters and university researchers to design, implement, and sustain a comprehensive cardiovascular disease prevention program tailored to the unique culture, work structure, and health risks of firefighters [8]. The partnership engaged firefighters as equal collaborators across all phases of the research process, from needs assessment to program evaluation. Firefighters initiated the collaboration; helped define priorities; administered department-wide health screenings; and were trained as peer fitness trainers to deliver physical activity interventions, advocate for policy change, and modify station environments to support fitness. This study demonstrates that capitalizing on firefighter social dynamics, governance, and professional skills builds sustainable trust between firefighters and researchers. Like Taylor et al, this approach offers a replicable model for collaboration between firefighters and academic researchers.

University-fire department collaborations can also benefit engineering instruction. According to the literature, inclusion of hands-on activities in Statics curricula using physical experiments and kits improves student learning compared to traditional lecture-based instruction. Davishahl et al used physical models in Statics that integrated concept-focused activities to build student competence with vectors and equilibrium concepts [9]. Using validated assessments to measure outcomes, these authors found that hands-on activities consistently demonstrated significantly larger student gains in vector representational competence than control sections without activities. Student feedback and instructor reflections further indicate that the physical kits enhanced student visualization, communication, and engagement when thoughtfully integrated into courses. These findings support the conclusion that hands-on Statics activities can meaningfully improve learning of core concepts when aligned with course structure and pedagogy.

Collectively, these studies demonstrate that durable university–community partnerships succeed when stakeholders serve as co-creators in defining priorities, shaping design decisions, and validating outcomes. This observation remains consistent regardless of whether the result is a policy instrument, a health intervention, a commercialized product, or an instructional innovation. Building on this reciprocal engagement and hands-on learning foundation, this paper's Theory section leverages engineering Statics principles to design and implement a functional spanned anchor simulator grounded in technical rigor and community relevance.

Gaps This Work Addresses

Before transitioning to theory, it is important to highlight gaps addressed by this current research. Currently, there is no firefighter accessible integration between their technical manuals and the underlying Statics. Existing manuals tabulate spanned anchor force multipliers but do not present the underlying equilibrium equations. This omission limits firefighter understanding of underlying physics and fails to represent all situations faced by rescuers in the field. For example, asymmetrical spanned anchor loading, a common field occurrence, is omitted from firefighter manual tables. This current work provides an equation of relevant variables quickly solvable by firefighters in the field to find spanned anchor force multipliers, addressing the gap in firefighter training materials. This current work also deploys a physical spanned anchor simulator training tool to build firefighter intuition, addressing the gap in university-firefighter community-engaged design for spanned anchor education.

Theory

The central danger in spanned anchor deployment is anchor point force induction far exceeding the weight of the person and gear being supported by the span. Understanding this counterintuitive result requires a free body diagram of simplified geometry, as shown in Figure 2.

Firefighters rapidly establish spanned anchors during emergencies when they must deploy over ledges. They do not have the luxury to measure every length and angle to determine forces on components. What they can measure quickly is the total length of the rope forming the anchor, $R = (r_1 + r_2)$, the distance between anchor points (L), the distance from one anchor to where the load is supported (y), and the span horizonal included angle (Θ). This is the angle subtended by the two rope subsections where the load is supported. A practical mathematical model easily solvable in the field (e.g., using a preprogrammed pocket computer or cell phone app) for the forces induced on the right and left anchors of a spanned anchor can only contain these four variables. The resulting equations and their derivation are given in the appendix.

In spanned anchor systems, as the angle Θ approaches 180° (a straight line), the theoretical tension in the rope approaches infinity. This is the origin of the extreme forces on anchor points many multiples of the weight being supported. To keep field calculations simple, firefighters use tabulated force multipliers:

the ratio of the rope tension to the tethered static weight. These multipliers are given in a field manual and tabulated based on Θ, which is measured or eyeballed during spanned anchor deployment before any weight is suspended from the anchor. Tabulated values assume the weight is suspended from the center of the span, but in reality, it can be shifted to the left or right of center to avoid obstacles on the roof / ledge where the anchor span is set up. Larger force multipliers imply larger rope tension and higher anchor force, which corresponds to greater safety risks for rescuers.

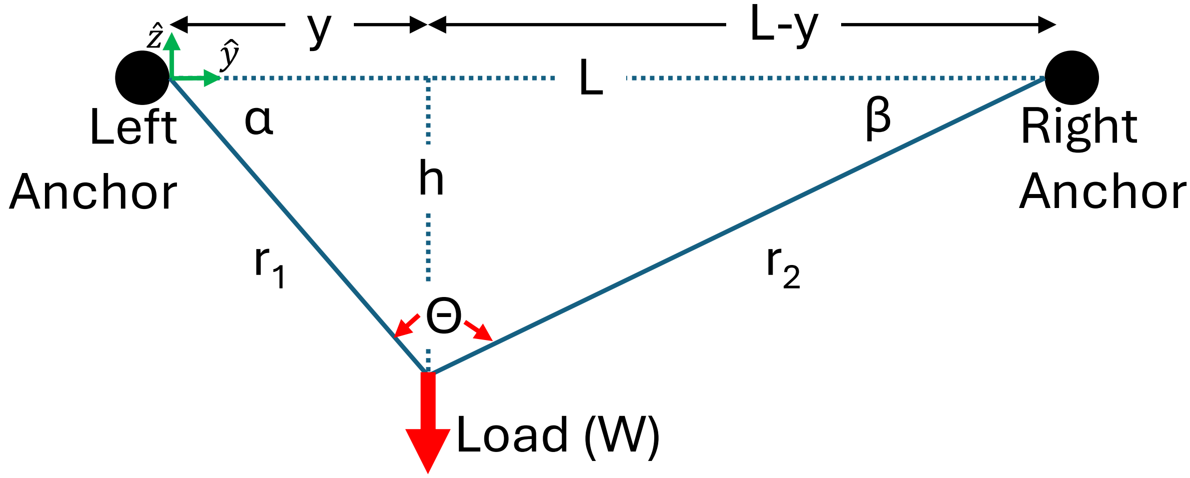

Figure 2: Free body diagram for a simplified spanned anchor showing anchor points, external forces, and geometric variables.

High force multipliers are problematic for two reasons: 1) they increase injury risk for the rescuer and victim during realistic events such as a slip or short fall and 2) they produce larger tension forces at each anchor reducing operating comfort and decreasing functionality. As a baseline, the target value used by GFR in spanned anchor setups is a force multiplier of approximately 1.3 at $\Theta = 135°$. For a 200-lbf firefighter, this rule of thumb corresponds to an estimated system load of 260 lbf (200 lbf × 1.3), which is then used to estimate anchor forces based on the span angle. Accordingly, the primary goal of this university-firefighter collaboration is identifying spanned anchor geometries that minimize the force multiplier while avoiding excessive rope slack. Early in the work, need for practical mapping between span angle and force multiplier was emphasized to support firefighter training – hence desire for a physical spanned anchor simulator teaching tool.

Methods

Spanned Anchor Simulator Teaching Tool Design

Materials required to construct a complete spanned anchor simulator are given in Table 1. A complete unit can be built for $48.20 from materials available through Amazon and Home Depot. Cost of physical hardware is important to promote the accessibility of hands-on experiments, especially if many copies are created for large enrollment firefighter training programs or for college classes where many students simultaneously access labs. Apparatus cost is also an important consideration for equipment acquisition by high schools wishing to facilitate hands-on experiences. As a point of comparison, the PASCO ME-6855 Tension Protractor carries out a generic tension education experiment identical to the spanned anchor simulator, and it retails for $169 [10]; over 3.5X the price. Armfield Engineering also produces its EFK1-MKII statics kit with similar capabilities, but Armfield does not publish prices.

For scratch built educational Statics kits, Davishahl and coauthors reported creation and deployment of their Statics Modeling Kit (SMK), which can also reproduce the spanned anchor configuration [11]. In 2018, materials per-unit to build an SMK cost $37.90. This sum equals $48.90 in 2026 dollars; about the same cost as the spanned anchor simulator device reported here. However, SMK is specifically for Statics student instruction, not for firefighters, and made from Polypropylene perf sheet, which is unlikely to stand up to rough handling over time.

Table 1: Spanned Anchor Simulator Parts List, Cost, and Sources

#	Description	Unit Cost	# Needed	Total Cost	Source
1	Digital Fishing Scale (110lb/50kg) with Backlit LCD, Portable Handle, Stainless Steel Hook & 2 AAA Batteries	$7.99	2	$15.98	https://www.amazon.com/gp/product/B0F155YPCZ
2	Double Hooked Chrome-Plated Hook Weight with Case, 4 Pcs 200g (0.44lbs)	$14.47	1	$14.47	https://www.amazon.com/gp/product/B0BJZHHRBQ
3	Digital 7-inch / 200-mm Protractor Angle Ruler	$8.49	1	$8.49	https://www.amazon.com/gp/product/B0F629CY6J
4	Nylon String #18 Braided Gauge Line, 250 ft	$6.28	1	$6.28	https://www.amazon.com/gp/product/B0D5468TYH
5	2 in. x 4 in. x 4 ft. #2 Premium Grade Dimensional Lumber	$2.98	1	$2.98	https://www.homedepot.com/p/ProWood-2-in-x-4-in-x-4-ft-2-Premium-Grade-Dimensional-Lumber-271736/300524962
				$48.20	**TOTAL**

Spanned Anchor Simulator Fabrication

Fabrication steps for the spanned anchor simulator are outlined in Figure 3. The system's manufacture requires little technical skill and can be accomplished using hand tools. The device is laid out on 4-foot-long 2 x 4 dimensional lumber, which can be marked with a sharpie. First (A), mark the lumber's centerline and scale anchor points 12 inches right and left from center. Second (B), mark with a sharpie the centers of the scales metal handles for drilling. Third (C), drill the metal scale handles with wood screw clearance holes and predrill lumber pilot holes at the scale attachment points. Fourth (D) screw the scales into the lumber with wood screws, and (E) the spanned anchor simulator is ready to use.

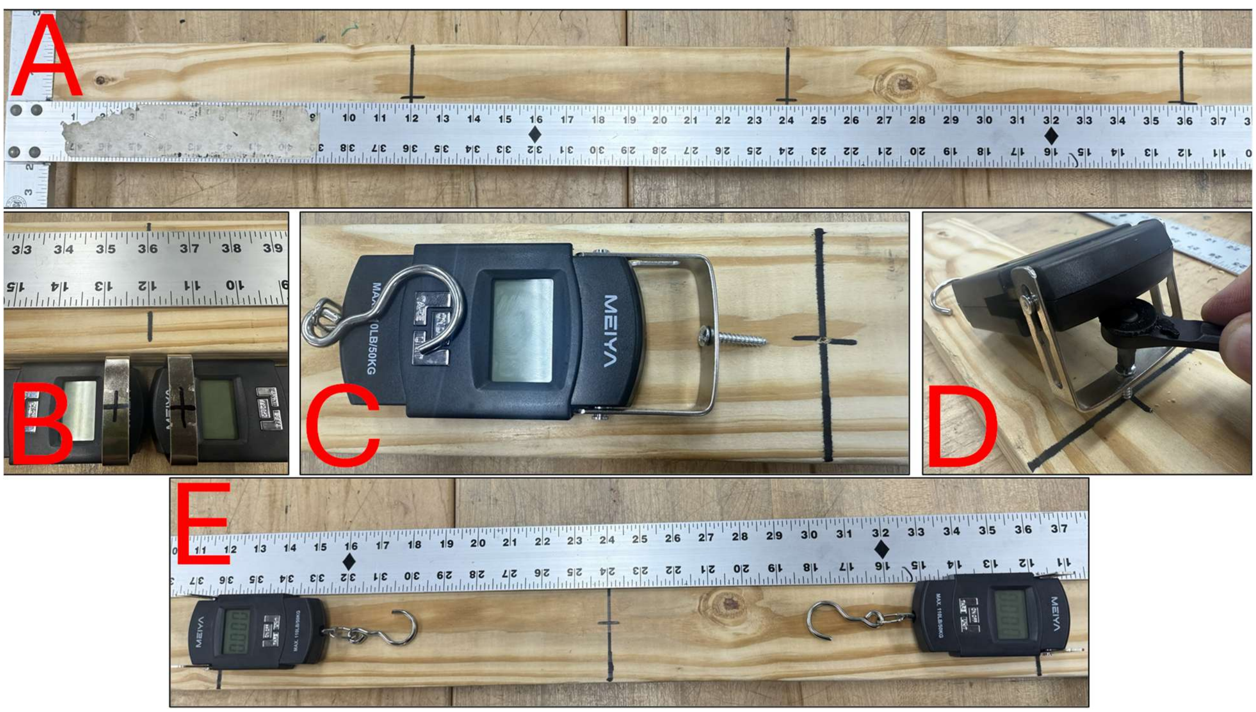

Figure 3: Steps to lay out the spanned anchor apparatus on 4-foot-long 2 x 4 dimensional lumber.

Variables in the Simulated System

The spanned anchor is set up to represent and measure dependent and independent variables of the full scale system important to the rescuer, as shown in Figure 4. A key outcome is determination of force multipliers at anchor points as a function of rope length, $R = (r_1 + r_2)$, distance between anchor points

(L), distance from one anchor to where the load is supported (y), and the span horizonal included angle (Θ) at the weight attachment point. The resulting measured multipliers are dimensionless force ratios. Geometric similarity of the spanned anchor simulator to the full-scale setup enables one-to-one correspondence between model and full-scale multipliers. What firefighters measure with the simulator is directly analogous to multipliers their system experiences in the field.

Figure 4 imposes a Statics free-body diagram first shown in Figure 2 onto the spanned anchor simulator rope to illustrate for firefighters how the physical simulator corresponds to the free body diagram and where are the critical dimensions to be measured. This approach makes Statics abstractions more tangible and improves the firefighter's intuition to predict system behavior from a given configuration.

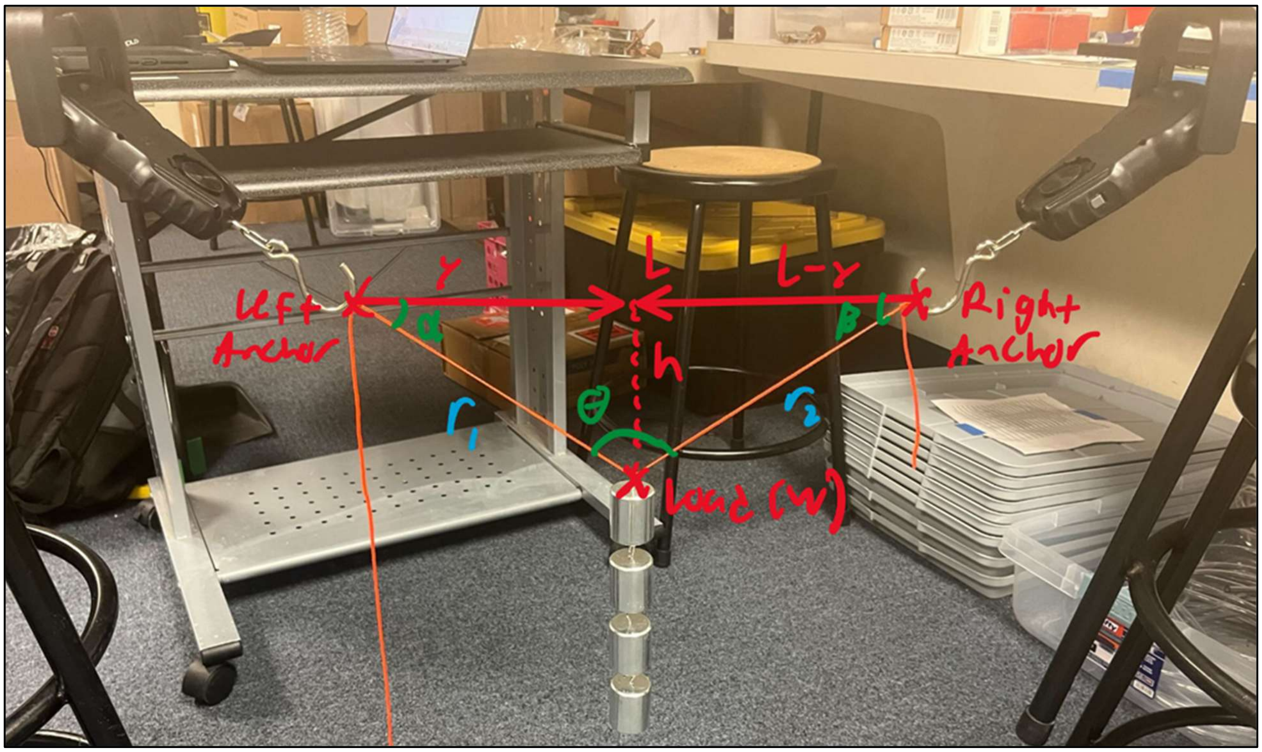

Figure 4: Free body diagram superimposed on the physical spanned anchor simulator under 800g load.

Figure 5 shows GFR firefighters working with UF MAE research students in a training session at the fire station to set up and test the spanned anchor simulator. This interaction illustrated effectiveness of best practices for university-fire department partnerships established in the literature. Equal partnership and respect for each other's expertise was illustrated when firefighters provided instruction on rope handling. The engineers struggled to keep the apparatus's weights stationary in asymmetrical configurations. The offset weights kept sliding down the rope to the equilibrium point, and various mechanical attachments were tried unsuccessfully. Applying their ropework experience, firefighters demonstrated that simply looping the rope twice over the weight hook provided ample friction to keep it in place without mechanical anchoring.

These interactions also provided opportunities for engineers to describe Statics concepts and for firefighters to repeat the same concepts in first responder jargon. These exchanges both improved firefighter understanding and taught engineers their collaborator's situated language. Iterative in-person engagement also proved beneficial with GFR firefighters and UF MAE researchers meeting in person three times during the initial collaborative trial. On each visit, additional understanding and rapport were built. Having a spanned anchor simulator physical prototype was another beneficial best practice from the literature. It helped the team converge upon shared language and established collective design and useability priorities for the full-scale system. Also, as indicated in the literature, the partnership benefitted from being initiated by GFR and led by a lieutenant and trainer who is a decorated senior leader highly respected throughout GFR. His example of engagement induced and encouraged younger firefighters in the training session to fully engage with UF MAE researchers.

Figure 5: Firefighters from GFR working with UF MAE research students on the simulated spanned anchor.

Spanned Anchor Full Scale System Testing

At their third meeting, GFR and UF MAE collaborators visited the GFR over-ledge training site where firefighters demonstrated deploying a full-scale spanned anchor, as shown in Figure 6 (Right). The training site is the roof of an 11-story apartment building in Gainesville, FL. From here firefighters and student researchers conducted a series of tests that varied span angle, applied load, and load position along the span. They also simulated realistic rescue scenarios, including a subject being retrieved by a rescuer using the spanned anchor system. Shown in Figure 6 (Right) is a dynamometer for measuring rope tension, which was placed in line with the spanned anchor. In both training and real scenarios, dynamometers are used by GFR to quickly measure the rescuer's initial weight and then monitor rope tension as the rescuer transitions over the ledge, supports the subject being rescued, and returns to safety. The dynamometer recorded tension force transmitted to the anchors throughout each trial. For static situations, these measured tensions produced force multipliers consistent with those predicted by the spanned anchor simulator, providing field validation and supporting the project's central claim.

Whereas the spanned anchor simulator represents a static idealization, over-ledge rescues place dynamic loads on spanned anchor components, which contribute to firefighter "factor of ignorance" about true forces experienced by their equipment. The dynamometer revealed its highest measured values while the rescuer was being pulled back up to the ledge's top. This observation suggests the pulling and lifting phase represents the highest-risk segment for this operation, and forces experienced here are likely underpredicted by the static spanned anchor simulator.

Safety for Full Scale System Testing

When performing over-ledge operations, the rescuer must wear a harness that tethers them to the spanned anchor system by securing a hook at the end of the rope to the front of their harness. As shown in Figure 7, rescuers must also wear protective gear including a helmet, gloves, and close-toed shoes. A radio is required for communication at all times. Enough tension must be maintained in all load-supporting ropes to minimize slack because excessive slack increases the risk of injury should the firefighter fall even a few feet while dismounting the ledge. Rescuers never stand on windows and must remain in constant communication with an instructor from the rooftop.

Performance Testing

The simulator produces a range of real rescue configurations, including variations in rope length, span angle, knot and tensioning methods, and resulting force multipliers. By adjusting these values and observing the measured force responses, firefighters can develop theories for how a given setup may behave, identify setups that reduce excessive loading, and select appropriate components for a safe and effective rescue. Integrating the physical simulator and its associated calculations into firefighter training manuals makes this instruction attainable and repeatable across fire departments.

Figure 6: A spanned anchor training session used an in-line dynamometer to measure rope tension.

Results

Spanned Anchor Simulator Feedback from Firefighters

From the firefighters' perspective, the spanned anchor simulator was most valuable to make otherwise abstract force distributions physically visible and immediately measurable, helping connect rope rescue training to real load-sharing behavior in spanned anchor systems. Training participants appreciated the hands-on, interactive nature of the device and the ability to observe how anchor angles and tension adjustments altered loads. However, usability considerations were critical: components needed to be durable, quick to reset, and clearly tied to operations rather than perceived as purely academic instrumentation. Firefighters emphasized that the simulator's value depended on its ability to reproduce the force multiplier ratios in training handbooks as well as the dynamometer measurements from rescue training. The simulator was viewed as a meaningful training asset after it bridged engineering Statics principles with practical firefighter experience under realistic conditions.

The immediate beneficial firefighter use of the spanned anchor simulator was verifying tabulated force multipliers published in their handbook. These multipliers appear as a function of horizontal included angle (Θ) formed between the spanned rope sections. The simulator was able to reproduce these values in a physical apparatus. Moreover, the tabulated multipliers were predicted by the Statics equation shown in this paper's appendix, which can be applied in the field as easily as tabulated handbook values. These observations built confidence among the firefighters that the simulator and equation could model and predict static forces on the full-scale system. Not tabulated in training handbooks are force multipliers for loads positioned asymmetrically on the spanned anchor. Nonetheless, off-center spanned anchor attachment is a common condition in real over-ledge rescue deployments. Realizing they had a new and accurate tool to predict forces on offset anchors, the firefighters began testing asymmetrical configurations on the simulator, resolving to test them at full scale.

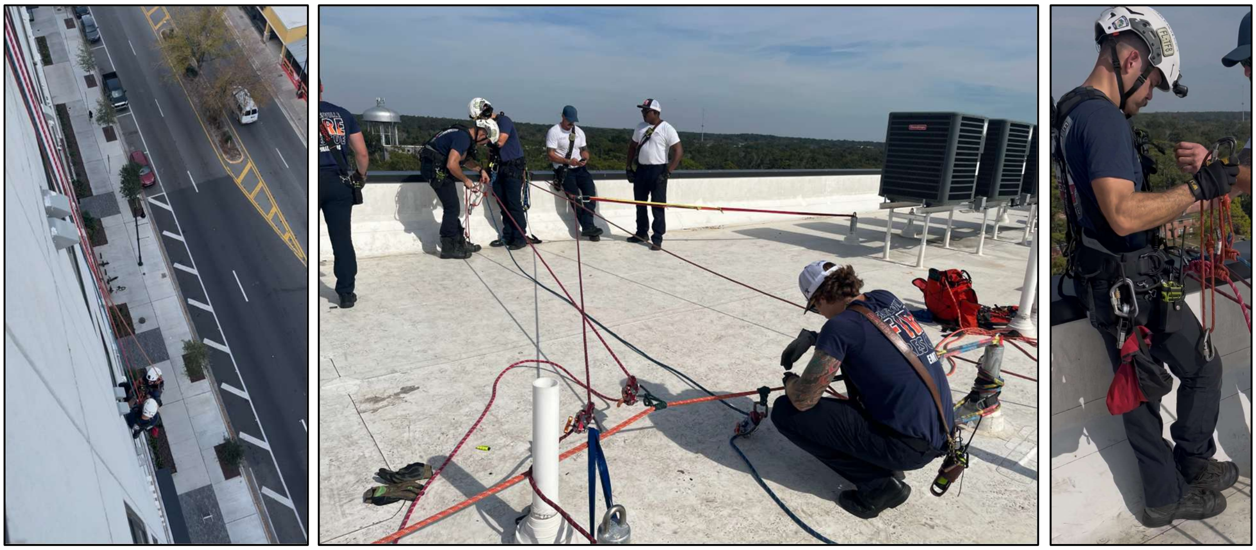

Figure 7: (Left) Over ledge rescuers in a practice session supported by a spanned anchor. (Center) The roof anchor points of the spanned anchor used during a GFR training session. (Right) Safety gear worn by firefighters during over-ledge operations.

Select Spanned Anchor Simulator Geometry & Load Results

Testing of the spanned anchor simulator was intentionally bounded to highlight operationally relevant configurations. When the load is shifted off-center, the anchor nearest the firefighter carries a greater share of the tension, but testing did not extend to extreme asymmetric placements beyond practical rescue conditions. At the upper limit, the tightest achievable configuration produced a horizontal included angle of approximately 160° (Figure 8 – Left), near the largest angles reported in field use. As expected, this configuration generated high force multipliers of 2.4–2.9 that were sensitive to small changes in load rendering this setup operationally unsafe in a full-scale system. Conversely, very shallow configurations with included angle of approximately 60° (Figure 8 – Right), produced low measured tension with force multiplier ≈ 0.59. While safer from a rope tension perspective, this configuration introduces excessive slack into the spanned anchor. Rope slack increases fall factor, the ratio of a rescuer's fall distance to the length of rope available to absorb that energy. Higher fall factors mean greater rescuer deceleration in a rope-arrested fall correlating to more injuries. This hazard is not quantifiable within the static benchtop spanned anchor simulator. Thus, while the simulator effectively captured key trends in force amplification and load redistribution, its testing envelope was constrained to static, controlled conditions that did not incorporate dynamic loading, which remain areas for future study.

Table 2 displays a subset of load results obtained for representative combinations of rope lengths (r_1, r_2), distance between anchor points (L), distance from one anchor to where the load is supported (y), and the span horizontal included angle (Θ). Also tabulated are corresponding results from the modeling equation (derived in the appendix), which show good agreement with experimental measurements.

Discussion

The results demonstrate that a low-cost, benchtop spanned anchor simulator can effectively reproduce the dominant force behaviors observed in full-scale firefighter rescue systems, while remaining accessible for both training and instructional use. Across all tested configurations, the simulator captured the nonintuitive relationship between span angle, rope geometry, and resulting tension forces; particularly the rapid increase in anchor forces as the span angle approaches a near-horizontal configuration. These behaviors are well known qualitatively within the firefighting community but are rarely quantified or directly measured during training. The ability to physically observe and measure these force changes in a controlled environment represents a significant advancement in both firefighter education and applied Statics instruction.

Table 2: Selected spanned anchor simulator loading results compared against the predictive Static equation.

Weight [grams]	L [cm]	y [cm]	r_1 [cm]	r_2 [cm]	Θ [°]	Experiment Left Anchor Force [N]	Predcited Right Anchor Force [N]	Experiment Left Anchor Force [N]	Predcited Right Anchor Force [N]
Center Loaded									
200	45	22.5	44	44	60	1.13	1.15	1.13	1.15
400	45	22.5	44	44	60	2.31	2.35	2.31	2.35
600	45	22.5	44	44	60	3.34	3.40	3.34	3.40
800	45	22.5	44	44	60	4.41	4.50	4.41	4.50
200	26	13.5	16	16	161	5.69	5.80	5.69	5.80
400	26	13.5	16	16	159	10.59	10.81	10.59	10.81
600	26	13.5	16	16	157	14.81	15.11	14.81	15.11
800	26	13.5	16	16	156	18.98	19.36	18.98	19.36
200	28	14	17	17	135	2.55	2.60	2.55	2.60
400	28	14	17	17	135	5.30	5.40	5.30	5.40
600	28	14	17	17	135	7.90	8.05	7.90	8.05
800	28	14	17	17	135	10.45	10.66	10.45	10.66
Left Loaded									
200	28	3	6	27	133	2.60	2.65	2.35	2.40
400	28	3	6	27	133	5.15	5.25	4.37	4.45
600	28	3	6	27	133	7.50	7.65	6.13	6.25
800	28	3	6	27	133	10.10	10.31	8.58	8.76

Load position along the span was also shown to meaningfully affect anchor force distribution. When the load was shifted closer to one anchor, that anchor experienced consistently higher tension, while the opposite anchor still carried a non-negligible share of the load. This behavior is particularly important operationally, as it challenges the assumption that only the nearest anchor governs system safety. In real rescue scenarios, where anchor quality may differ due to structural conditions, understanding this asymmetric load sharing can guide anchor selection, redundancy decisions, and component placement.

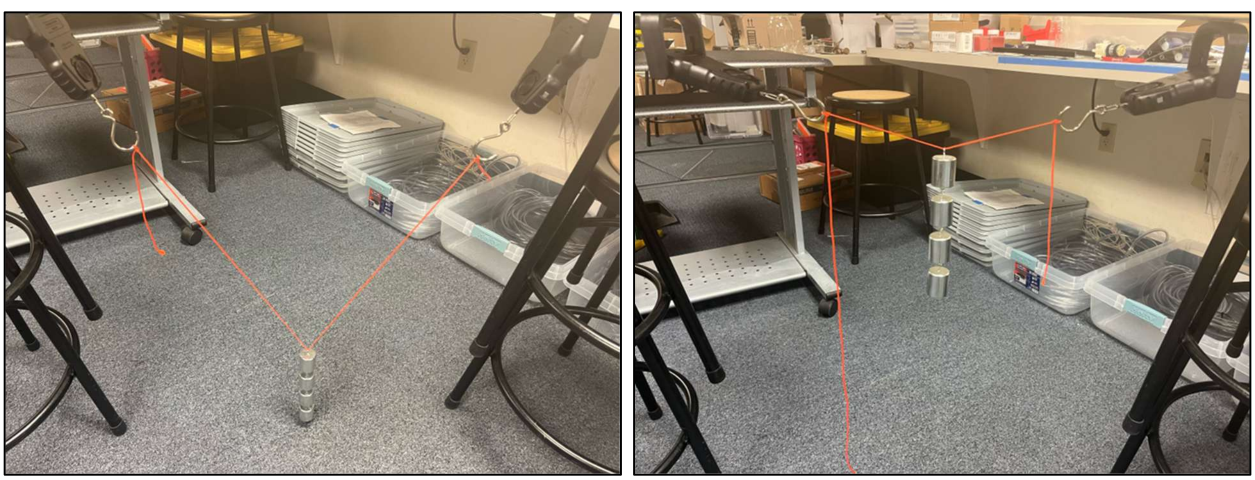

Figure 8: Loaded spanned anchor simulator measuring anchor forces at (Left) Θ = 60° and (Right) Θ = 160°, the two extreme horizontal included angles used in this study.

One of the most important findings is the relative stability of the force multiplier for a given configuration. For example, at approximately 135°, the simulator consistently produced a force multiplier near 1.3 across a wide range of applied loads. This finding reinforces a critical conceptual point: while firefighter body weight affects absolute tension forces, the force multiplier is primarily governed by system geometry rather than weight alone. This insight directly addresses the long-standing "factor of ignorance" described by firefighters, where conservative assumptions lead to substantial overdesign and unnecessary carried weight. By tying force amplification explicitly to measurable geometric parameters, the simulator enables more informed decision-making without sacrificing safety margins.

The simulator further highlights the operational risks associated with extreme configurations. Near-horizontal span line setups ($\Theta \approx 160°$) produced force multipliers approaching or exceeding 2.5, with high sensitivity to small changes in load and geometry. These configurations were not only associated with unacceptably high force multiplication factors but also exhibited instability, where minor variations in applied load resulted in noticeable shifts in measured angle and tension. From a training perspective, this instability is arguably as important as the absolute force values, as it underscores why such configurations are impractical and dangerous in real operations. Conversely, very low-angle configurations ($\Theta \approx 60°$) produced low force multipliers but introduced excessive slack, increasing fall factor risk. Together, these results reinforce the idea that "safe" spanned anchor setups occupy a relatively narrow operational window that balances force amplification against slack-related hazards.

<u>Simulator Use as a Collegiate Statics Educational Tool</u>

Beyond firefighter training, the simulator offers clear educational value in undergraduate statics courses. The spanned anchor problem is an ideal example of a system where intuitive reasoning often fails, making it difficult for students to internalize equilibrium concepts through equations alone. By allowing learners to physically manipulate geometry, measure forces in real time, and compare observations with analytical predictions, the simulator supports development of representational competence and conceptual understanding. This finding aligns closely with prior findings in engineering education literature showing that hands-on, concept-focused activities improve student learning outcomes when thoughtfully integrated into coursework.

As of this manuscript, use of the spanned anchor simulator as a hands-on element in a college Statics course or high school physics class remains aspirational and has not yet been implemented. We plan to co-develop a curriculum with a Statics instructor that involves either a video showcasing GFR's spanned anchor use, a classroom visit by GFR, or a site visit to their training facility. The plan is for firefighters to talk about real world deployment of the spanned anchor for rescues to add an applied element to the theoretical and small scaled experimental learning in a Statics course. Given the economical, reusable, and robust nature of the spanned anchor experiment another opportunity for dissemination is piggybacking into an existing national kit-based statics instruction conglomerate like Newton's Team. This consortium created a series of portable hands-on learning activities that use simple materials. Each activity requires very little preparation time and can be implemented within online or in-person instructional modalities [12].

<u>Firefighter – University Collaboration</u>

Equally important is the collaborative process through which the simulator was developed. Firefighters served not merely as end users but as co-designers, shaping the simulator's form, measurement approach, and instructional goals. This ensured that the device addressed real operational questions, used firefighter-relevant language, and prioritized simplicity and robustness over unnecessary complexity. The resulting system functions as both an engineering theory demonstrator and an emergency responder trainer, enabling mutual learning and sustained collaboration.

Finally, the simulator provides a foundation for future work. While the present study focused on static loading, the observed fluctuations during over-ledge rescuer lifting operations point to the importance of dynamic effects that merit further investigation. Additionally, systematic exploration of load limiter behavior, knot efficiency, and component variability could further refine training guidance. From an educational perspective, the simulator could be incorporated into formal laboratory modules, outreach activities, or interdisciplinary courses that connect engineering students with first responders. In all cases, the core contribution remains the same: a simple, low-cost physical system that makes invisible forces visible, supports safer firefighter operations, and strengthens the connection between engineering theory and real-world application.

Conclusion

A low-cost, benchtop spanned anchor simulator was successfully designed, constructed, and validated through a collaborative effort between University of Florida researchers and Gainesville Fire Rescue. This partnership demonstrated that complex firefighter rescue systems can be effectively represented using simple, scalable physical models without sacrificing fidelity to the governing mechanics. The simulator reproduced key force behaviors observed in full-scale spanned anchor systems, including the nonintuitive amplification of anchor forces as the span angle approaches horizontal.

For operationally preferred configurations near $\Theta \approx 135°$, the simulator consistently produced a force multiplier of approximately 1.3, in close agreement with the analytical statics model and the tabulated values provided in the firefighter field guide. This result validates the current field heuristics used by GFR and reinforces the reliability of established field guidelines under symmetrical loading conditions. When the load position was shifted along the span, the simulator revealed asymmetric redistribution of anchor forces, with the anchor nearest the load carrying a greater proportion of the total force. Both the mathematical model and experimental measurements confirm this behavior, which is not addressed in the GFR field handbook, as it assumes centered, symmetrical loading. This added information from the spanned anchor simulator and the Static analysis is valuable to rescuers to provide force estimates in nonsymmetrical situations often faced during real rescues. Beyond validating analytical predictions and field guidance, the simulator provides firefighters with a tactile, visible, and directly measurable understanding of the statics principles governing spanned anchor systems, without requiring formal engineering calculations.

As an instructional tool, the spanned anchor simulator will also offer value in undergraduate Statics education by enabling students to physically connect free-body diagrams, equilibrium equations, and real force measurements within a meaningful real-world firefighting context. Finally, the co-design process between university researchers and firefighters followed best practices from the community-engaged design literature, establishing trust and shared ownership that form the foundation for sustained, multi-project collaboration.

Actionable Next Step Recommendations

The following actionable next steps are being pursued by GFR and UF MAE collaborators to continue their partnership and expand this valuable project. First, we will create a "safe operating window" guide for GFR using the existing benchtop and rooftop datasets to generate a simple decision aid (span angle Θ ranges, allowable offset ranges, and expected force multipliers/anchor load splits). This guide will be programmed into a pocket computer or cell phone app for the field, allowing GFR firefighters at a rescue scene to quickly input measured parameters and determine if spanned anchor load is safe for rescuer deployment. This action directly leverages the team's new asymmetric-loading force multiplier prediction capability into field-ready guidance.

Second, we will conduct a focused follow-on study on peak loads during the rescuer lifting phase (dynamic amplification), which was anecdotally observed to produce the highest dynamometer forces during training. GFR and UF MAE partners will design a repeatable protocol including controlled raise rates, short slip/edge-transition events, and different slack levels. This action's outcomes will be to quantify peak-to-static load ratios to better define safety envelopes and identify practices that reduce dynamic load spikes.

Third, we will package the spanned anchor simulator into a classroom deployable teaching module for engineering statics education. Development will include a curriculum, worksheet or lab manual, a data collection table, and a short hands-on activity challenging students to compare experimental measurements from the spanned anchor simulator to the underlying Statics equations. We will record a video with GFR firefighters who will talk about the real world spanned anchor deployments and showcase an over-ledge rescue practiced in training. This video can be played for students to connect their classroom learning to an important real-world application.

Appendix: Spanned Anchor Force Derivation

The following derivation steps through the process of determining the right and left anchor forces, T_1 and T_2 in terms only of the values firefighters can directly measure for a spanned anchor: W, R, L, y, and Θ. All other variables are eliminated through trigonometry and clever substitution. The geometry is given in Figure 1. In this derivation, the rope is assumed to be of negligible mass and to hang with no curvature. L is the horizontal anchor-to-anchor distance; R is the total rope length where $R > L$; y is the horizontal distance from the left anchor to the load attachment spot, which is constrained by $0 < y < L$; and W is the load force being supported. The rope angles from horizontal at the left and right anchor points are α and β respectively, but since these angles cannot be measured in the field, they must be substituted away in the final equation set for Θ, which can be measured.

For the triangle made between the anchor points and the load:

$$\alpha + \beta + \Theta = 180° \tag{1}$$

Due to the π periodicity of the sine function, the supplementary angle identity gives:

$$\sin(\alpha + \beta) = \sin(\Theta) \tag{2}$$

From the sine angle-sum identity:

$$\sin(\alpha + \beta) = \sin(\alpha)\cos(\beta) + \cos(\alpha)\sin(\beta) \tag{3}$$

From a Free Body Diagram applied to the weight attachment point on the rope:

$$\sum F_x = T_1 \cos(\alpha) - T_2 \cos(\beta) = 0 \tag{4}$$

$$\sum F_y = T_1 \sin(\alpha) + T_2 \sin(\beta) - W = 0 \tag{5}$$

Solving Eq. (4) for T_2 gives:

$$T_2 = \frac{T_1 \cos(\alpha)}{\cos(\beta)} \tag{6}$$

Plugging this result into Eq. (5) gives:

$$T_1 \sin(\alpha) + \frac{T_1 \cos(\alpha)}{\cos(\beta)} \sin(\beta) = W \tag{7}$$

By the sine angle-sum identity, Eq. (7) simplifies to:

$$T_1 \frac{\sin(\alpha + \beta)}{\cos(\beta)} = W \tag{8}$$

Rearranging Eq. (8) and using the relationship in Eqs. (2) and (6) gives:

$$T_1 = W \frac{\cos(\beta)}{\sin(\Theta)} \tag{9}$$

$$T_2 = W \frac{\cos(\alpha)}{\sin(\Theta)} \tag{10}$$

From trigonometry:

$$\cos(\beta) = \frac{L - y}{r_2} \tag{11}$$

$$\cos(\alpha) = \frac{y}{r_1} \tag{12}$$

Substituting Eq. (11) in Eq (9) and substituting Eq. (12) into Eq. (10) gives:

$$T_1 = \frac{W(L - y)}{r_2 \sin(\Theta)} \tag{13}$$

$$T_2 = \frac{Wy}{r_1 \sin(\Theta)} \tag{14}$$

By definition, the rope segments equal the rope's total length:

$$r_1 + r_2 = R \tag{15}$$

From the Pythagorean theorem:

$$r_1^2 = y^2 + h^2 \tag{16}$$

$$r_2^2 = (L - y)^2 + h^2 \tag{17}$$

Adding Eq. (16) and Eq. (17) and simplifying gives:

$$r_1^2 - r_2^2 = y^2 - (L - y)^2 \tag{18}$$

$$r_1^2 - r_2^2 = L(2y - L) \tag{19}$$

Factoring Eq. (19) gives:

$$(r_1 - r_2)(r_1 + r_2) = L(2y - L) \tag{20}$$

Algebraic manipulation and substitution gives:

$$(r_1 - r_2) = \frac{L(2y - L)}{R} \tag{21}$$

$$(r_1 + r_2) + (r_1 - r_2) = R + \frac{L(2y - L)}{R} \tag{22}$$

$$2r_1 = R + \frac{L(2y - L)}{R} \tag{23}$$

$$r_1 = \frac{R^2 + 2Ly - L^2}{2R} \tag{24}$$

$$r_2 = \frac{R^2 - 2Ly + L^2}{2R} \tag{25}$$

Plugging Eq. (24) in Eq. (13) and Eq. (25) into Eq. (14) gives the desired formulas

$$T_1 = \frac{2WR(L - y)}{\sin(\Theta)\,[R^2 - 2Ly + L^2]} \tag{26}$$

$$T_2 = \frac{2WRy}{\sin(\Theta)\,[R^2 + 2Ly - L^2]} \tag{27}$$

Tabulated spanned anchor force multipliers in firefighter field guides are organized by Θ, the horizontal included angle made by the spanned anchor rope segments and measured at the weight anchor point. This is an angle firefighters can measure directly. So, to maintain user familiarity, Eq. (26) and Eq. (27) will be used to calculate anchor forces T_1 and T_2 induced by rope tension. However, Θ can be calculated in terms of the other independent variables through Law of Cosines and given geometry:

$$\Theta = \cos^{-1}\left[1 - \frac{2L^2R^2}{R^4 - L^2(2y - L)^2}\right] \tag{28}$$

Thus, if desired, Θ could be eliminated from calculations, leaving $T_{1,2} = f(\mathrm{W, R, L, y})$ only.

References

[1] Oerther, D. B. (2022) "A Case Study of Community-Engaged Design: Creating Parametric Insurance to Meet the Safety Needs of Fisherfolk in the Caribbean," *Journal of Environmental Engineering*, Vol. 148, No. 3, Article 05021008.

[2] Koh, R. (2020) "Engagement In Practice: Community Engaged Capstone Design Experience," *Proceedings of the ASEE Virtual Annual Conference*, Virtual Online.

[3]Traum, M. J., Jariwala, A. S., Emert, R. A., Aliperti, C. C., DeCostanza, A. H. (2024) "Accelerating Army Tactical Innovation: A Five-way University-Military-Government-Nonprofit Collaboration to Speed Soldier-Ideated Technology Development," *Proceedings of the American Society for Engineering Education Southeastern Section Conference,* Marietta, GA, USA.

[4]Swanson, T. R., Collins, J. M., Frey, J., Zocher, J., Traum, M. J. (2014) "Four-Way Collaboration Between a Non-Profit, University, Honor Society, and Charter School to Engineer Tropism Machines for Sustainable Space Nutrition Classroom Instruction (Work In Progress)," *Proceedings of the American Society for Engineering Education Conference and Exposition*, Indianapolis, IN, USA.

[5] Lombard, S., Recsnik, M., Reynolds, M., Toland, J., Traum, M. J. (2011) "Time-Based Bounding Values For Blower Door Infiltration Measurements In Buildings With Compromised Envelope Tightness," *Proceedings of the American Society for Engineering Education Gulf-Southwest Annual Conference*, Houston, TX, USA.

[6] Taylor, R., Macy, G., Hwang, J., Golla, V., Cann, C., Sanyang, E. (2022) "Using Collaborative Partnerships to Engage Firefighters in Rural Communities," *International Journal of Environmental Research and Public Health*, Vol. 19, No. 4, pp. 2009.

[7] Walden, R., Lie, S. (2020) "University–industry collaboration in frugal innovation through prototyping: The case of a firefighter cooling vest," *IEEE Transactions on Engineering Management*, Vol. 68, No. 3, pp.725-738.
[8] Delisle, A. T., Delisle, A. L., Chaney, B. H., Stopka, C. B., Northcutt, W. (2013) "Methods for fostering a community academic partnership in a firefighter community," *American Journal of Health Behavior*, Vol. 37, No. 6, pp. 721-733.
[9] Davishahl, E., Zhang, A., Chen, J., Rupe, K. M. (2024) "Can Hands-on Statics Improve Student Learning?" *Proceedings of the American Society for Engineering Education Annual Conference & Exposition*.
[10] PASCO, ME-6855 Tension Protractor product information page. URL: https://www.pasco.com/products/lab-apparatus/mechanics/statics-materials-and-strain/tension-protractor (accessed 2/21/2026).
[11] Davishahl, E., Pearce, R., Haskell, T. R., Clarks, K. J. (2018) "Statics Modeling Kit: Hands-On Learning in the Flipped Classroom," *Proceedings of the American Society for Engineering Education Annual Conference & Exposition*, Salt Lake City, UT, USA.
[12] Goble C.F., Grady, M.E. (2025) "Six Statics Activities in a Shoebox Kit," *Proceedings of the American Society for Engineering Education Annual Conference & Exposition*, Montreal, Quebec, Canada.