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FORCE STABLE RECONFIGURABLE TRUSS STRUCTURES USING QUADRILATERAL LINKAGE PRINCIPLES

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Abstract
Trusses are valued for their simple design principles and efficient load-bearing capability. However, slow member-by-member assembly and static topology restrict rapid deployment and reconfiguration of trusses for functional use. While mechanical linkages offer rapid deployability and reconfigurability, their scalability for large-scale civil structures is often constrained by the characteristics of their unit cells. These limitations raise the question: Can the design versatility of trusses be combined with the kinematic advantages of mechanical linkages to create structurally efficient, force-stable, scalable, deployable, and reconfigurable systems? To that end, we present a method inspired by flat-foldable quadrilateral linkages to transform static trusses into compactly stowable, reconfigurable systems. An additional node is introduced on the tensile members of triangular units with the help of Grashof linkage principles. This node converts triangles into flat-foldable quadrilateral linkages, enabling system-level reconfigurability while preserving the structure's load capacity, stiffness and stability. We show that the Fink, Scissor, and Warren trusses can be transformed into reconfigurable systems, achieving up to 93% and 60% reduction in convex hull area and maximum length, respectively, upon actuation of all degrees of freedom. Proof-of-concept prototypes, including a reconfigurable cantilever and a three-meter Warren truss bridge, validate feasibility while demonstrating load capacities and stiffness comparable to their static counterparts. We believe the proposed method will advance the design, analysis and fabrication of sophisticated bar-linked reconfigurable structures with potential applications in deployable infrastructure for aerospace systems, robotic components, metamaterials, and more.

Keywords: Reconfigurable trusses; Four-bar linkages; Shape-morphing trusses; Force-stable trusses

1. Background on reconfigurable trusses

Trusses have utilized a simple engineering concept of arranging structural elements in a network of triangles to create stable, load-bearing structures for over 5000 years[1]. Over time, the adoption of new materials and advancements in analysis, design and construction techniques have enabled engineers to design trusses tailored for diverse geometries, loads, and support conditions. Despite these advances, *modern trusses lack reconfigurability*. The static nature of trusses and the slow member-by-member assembly process prevent rapid deployment and shape morphing for functional use. These limitations highlight the need for methods that make static trusses reconfigurable and maintain structural integrity.

The need for reconfigurable structures has motivated extensive research into various bar-linked mechanical linkages. Examples include Scissor linkages[2], overconstrained mechanisms such as Bricard[3] linkages, tensegrity structures[4], and more. These bar-linked mechanisms have been used to create deployable structures for applications ranging from retractable arches to space systems. However, most design approaches begin by developing a deployable unit, which is then assembled into a larger system. While this bottom-up approach has proven effective, the overall system behaviour is often constrained by the characteristics and limitations of its fundamental unit. In contrast, starting with a desired static bar-linked structure and modifying its members to incorporate a mechanism offers broader design possibilities for reconfigurable systems. A handful of studies have explored ad hoc substitution of rigid truss members with alternatives such as telescoping beams[5], scissor linkages[6], cable elements[7], or semi-rigid joints[8] to enable structural transformations. However, these methods lead to limited transformation ranges, reduced deployment efficiency, complex actuation mechanisms, and increased fabrication complexity. Existing approaches lack a generalised framework that can applied to a broad range of static trusses and transform them into deployable, scalable and efficient reconfigurable systems.

This paper introduces a method to convert static trusses with a series of triangles into foldable, reconfigurable systems. Our method strategically introduces a new node within each triangular unit of a truss and converts it into a reconfigurable quadrilateral linkage. The placement of these new nodes is guided by the flat-foldability criterion for planar Grashof[9] quadrilateral linkages, the geometry of the triangular unit, and the force characteristics of the truss members. We apply this approach to transform three conventional static trusses into reconfigurable systems and demonstrate their ability for compact storage and reconfigurability. We also present proof-of-concept prototypes of the modified trusses to highlight scalability, force-stability and the ability to maintain structural performance comparable to static trusses.

2. How to get reconfigurable trusses?

The proposed method transforms a static truss into a reconfigurable system by converting its triangular units into quadrilateral linkages through the introduction of an additional node. The position of this node is determined to satisfy the Grashof condition in the resulting quadrilateral linakge. According to the Grashof condition, the linkage permits full rotation of the shortest link with respect to the adjacent links if the sum of the shortest (S) and the longest (L) links is less than or equal to the sum of the other two links (P & Q). The linkage folds flat and achieves maximum compactness when the node placement fulfils the *flat-foldability criterion*, expressed as $\boldsymbol{S + L = P + Q}$ and shown in Figure 1(a).

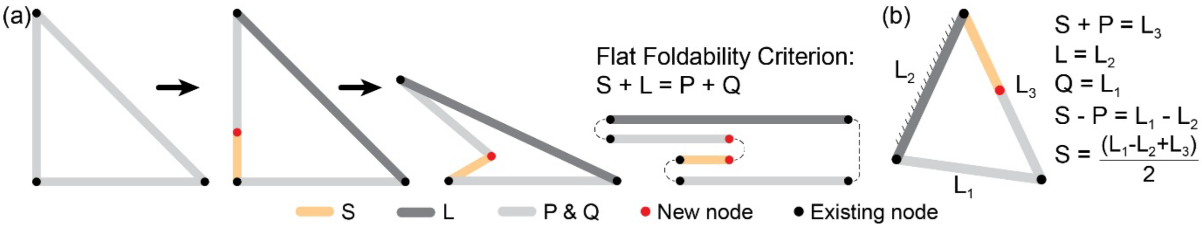

Figure 1. (a) Decomposing a triangle into a Grashof quadrilateral linkage using the flat-foldability criterion; (b) Length of the shortest link in the newly formed quadrilateral linkage to determine node location in a triangular unit. **Note:** The Ground link is shown with a hatched side and $L_1 < L_2 < L_3$.

2.1. Determining node location in an individual triangle

The new node's location depends on the member lengths of the triangular unit. We define the Ground link as the member that remains fixed relative to the moving links of the resulting quadrilateral linkage and the Candidate link as the member split by the new node. The node is positioned along the Candidate link at a distance S from the Ground link. This length S is derived to satisfy the flat-foldability criterion and allow the linkage to fold flat relative to the Ground link. The shortest link is always placed adjacent to the Ground link for consistency. Figure 1(b) illustrates the derivation of length S for one combination of Candidate and Ground links in a scalene triangle. Applying this method across all triangle types and Ground–Candidate link combinations results in *13 distinct ways* to convert a triangular unit into a flat-foldable quadrilateral linkage.

2.2. Unit-level to system-level reconfigurability

System-level reconfigurability in a static truss is achieved by introducing a node in each triangular unit one by one. We assume statically determinate trusses with a single continuous series of triangles between the top and bottom chords. In each triangle, the Ground link is the side shared with the previous triangle, and the Avoid link is the side shared with the next. The remaining side becomes a Candidate link if it is in tension, and a node is placed on it according to the criteria described in Section 2.1. This process continues triangle-by-triangle. When the current and next triangles are congruent, and the shared side is tensile, a node is placed on the shared side to create a 6-bar linkage with a single degree of freedom (DOF). A triangle is skipped if a node has been placed on its Ground link in a previous step or if neither of the sides (excluding the Ground link) is tensile. If the first triangle lacks two supports to identify the Ground link, the compressive member, excluding the side shared with the next triangle, is labelled as the Ground link. Each new node adds an independent kinematic DOF to the truss. Only tensile members are chosen as Candidate links since the resulting decomposed links require no additional locking of joints and remain force-stable under external loads. This approach also preserves the structural stiffness and load capacity. Splitting compressive members requires locking of joints as minor imperfections could lead to buckling failure. Hence, compressive members are **not** chosen as Candidate links.

3. Transforming traditional trusses into reconfigurable systems

This section demonstrates the transformation of static (a) Scissor, (b) Fink, and (c) Warren trusses into reconfigurable systems and examines their movement in space. A sequential kinematic simulator, developed using the analytical solution of planar quadrilateral linkages[10], helps visualize the kinematic path of the structure by actuating each degree of freedom (DOF) individually. Users can specify the extent of actuation of each DOF from 0% (initial state where the decomposed links of the Candidate link are collinear) to 100% (fully flat-folded configuration). The packing density of the structure during shape transformation is evaluated by tracking two parameters: (i) Normalized convex hull area - the area of the smallest convex shape enclosing all truss nodes, expressed as a multiple of the convex hull area in the fully deployed state, and (ii) Normalized maximum length - the largest distance between any two points within the convex hull, expressed as a multiple of the maximum length in the fully deployed state.

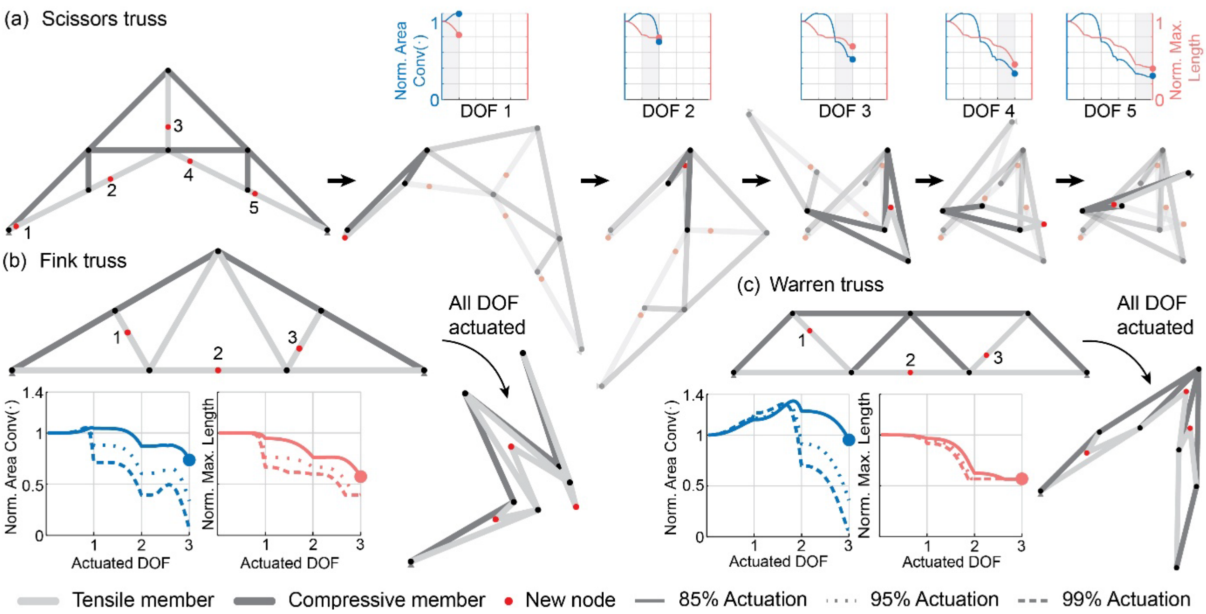

Figure 2. (a) Sequential actuation of each kinematic DOF up to 85% of a reconfigurable Scissor truss. The dual Y-axis plots display changes in the normalized convex hull area (left axis) and the normalized maximum length of the truss (right axis) as the truss morphs. The initial and final state after actuating each kinematic DOF up to 85% for the (b) Fink and (c) Warren truss, along with the normalized convex hull area and normalized maximum length plots for 85%, 95% and 99% actuation of each DOF.

Figure 2(a) demonstrates the sequential actuation of the DOFs in the reconfigurable Scissor truss obtained using the proposed methods. The five independent DOFs are actuated up to 85% of their maximum limits to enhance visualization. Despite this partial actuation of the DOFs, the Scissor truss achieves a convex hull area and a maximum length of approximately 0.3 and 0.4 times their respective values in the fully deployed state. Actuating the DOFs of the Fink truss (Figure 2b) up to 85%, 95%, and 99% of their maximum limits reduces the normalized convex hull area to 0.73, 0.34, and 0.07, respectively. However, the normalized maximum length plateaus at a value of 0.39. For the Warren truss (Figure 2c), the actuation of all DOFs up to 85%, 95%, and 99% of their maximum limits reduces to convex hull area to 0.95, 0.36, and 0.07, respectively, while the normalized maximum length plateaus at a value of 0.56. The overall compactness of the structure depends on the truss geometry and actuation extent. *Theoretically, the proposed method can achieve up to a 93% reduction in the structure's area and up to a 60% reduction in its maximum length at high actuation levels*. However, practical constraints, such as member overlap and contact, must be considered carefully before fabricating real-life reconfigurable truss structures.

4. Stiffness and strength comparison between reconfigurable and static trusses

Proof-of-concept prototypes of the static and reconfigurable cantilever truss (Figure 3a) were fabricated to demonstrate the structural performance and force-stable nature of reconfigurable trusses. Truss members were laser-cut from medium-density fiberboards and assembled into a two-ply arrangement using machine screws that permit member rotation. Load testing on three samples of each configuration (Figure 3b) revealed that the reconfigurable truss had a higher average peak load (433 N) but lower stiffness (32.06 N/mm) than the static truss (387 N, 42.32 N/mm). Both prototypes exhibited significantly lower peak loads and stiffness than theoretical predictions (725 N, 241 N/mm) for tensile member failure. The differences between the static and reconfigurable truss results can be explained by joint slipping and increased gravitational resistance due to additional material in the reconfigurable truss prototypes. We also believe that the significant difference between the observed and theoretical structural performance is due to material degradation from high-temperature laser cutting and fabrication-related joint play. *Overall, the reconfigurable truss demonstrated stable load-bearing capabilities, and both static and reconfigurable trusses exhibited comparable structural performance for all practical purposes.*

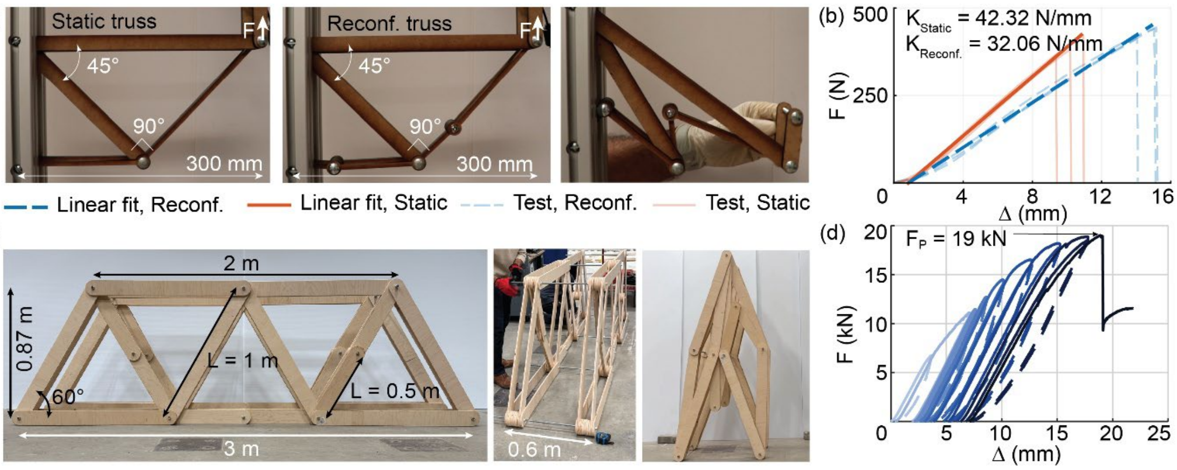

Figure 3. (a) Cantilever truss prototypes: static (left), deployed reconfigurable (middle) and stowed reconfigurable (right) truss. (b) Load-displacement curves for the static and reconfigurable cantilever trusses. (c) Reconfigurable Warren truss bridge: deployed (left and middle) and stowed (right) state. (d) Load-displacement curve of a three-point loading test on the reconfigurable Warren truss bridge. Darker colour shade of the curve represents higher specified displacement in each loading cycle.

A three-meter-long reconfigurable Warren truss bridge (Figure 3c) was fabricated to demonstrate the scalability of reconfigurable truss structures. Truss members were cut out of Maple plywood and assembled into a four-ply configuration (Figure 3c, middle) using threaded metal rods that permit member rotation. A cyclic three-point loading test evaluated structural behaviour under incremental displacements of 3.6 mm, 7.1 mm, 7.6 mm, 8.6 mm, 10.2 mm, 12.7 mm, 15.3 mm, 17.8 mm, and 20 mm. The load-displacement response (Figure 3d) reveals that the structure supported a peak load of 19 kN before failure by buckling of one of the compressive members. The observed peak load was lower than the theoretical peak load of 21.9 kN, which assumed failure due to tensile member fracture, with compressive forces remaining within yield and buckling limits. The buckling failure is likely due to fabrication imperfections, uneven cable tension in lateral bracing, and increased curvature in plywood members caused by moisture loss. Despite fabrication defects, the reconfigurable truss bridge demonstrated structural performance comparable to theoretical estimates. This outcome suggests that future design and fabrication improvements will lead to reconfigurable trusses performing as effectively as static trusses.

5. Conclusions

This paper introduces a general framework for transforming static trusses into deployable and reconfigurable systems. The framework draws inspiration from flat-foldable Grashof quadrilateral linkages to introduce an additional node in each triangular unit of static trusses based on the flat-foldability criterion, triangle geometry and member forces. This method ensures global system reconfigurability without compromising structural stiffness and load capacity. The effectiveness of this approach is demonstrated by transforming Scissor, Fink, and Warren trusses into reconfigurable systems that achieve up to 93% and 60% reduction in convex hull area and maximum structural length, respectively. Load tests on proof-of-concept prototypes of reconfigurable cantilever and Warren truss validate the method's feasibility in creating scalable, reconfigurable systems with structural performance comparable to static trusses. This framework opens new avenues for designing advanced deployable and reconfigurable bar-linked structures for applications in aerospace, robotics, metamaterials and more.

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