Modular Slotted Extruded Aluminum: Common T-Slot vs AngleLock™ Profile and Connectors Static Analysis

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Introduction

Slotted extruded aluminum framing is a commonly used product in several industries. The most common slotted extruded aluminum is known as T-slot extruded aluminum. T-slot aluminum has specific applications in machine frames and workstations, automation systems, exhibits and displays, robotics and prototyping, structural framing, safety and perimeter guards, stairs, platforms, and material handling carts [1], [2]. Note that this is not an exhaustive list of applications, only a few examples.

Some reasons T-slot modular aluminum framing structures are often used are because of their ability to be adjusted easily, disassembled for ease of shipping, and parts can be reused if the structure is no longer needed. No special skills are needed to assemble or take apart a structure made from T-slot extruded aluminum and most T-slot structures can be fully assembled using basic tools [3], [4].

For the applications listed, there are alternatives to T-slot extruded aluminum such as welded frames made from steel or possibly aluminum or tube and joint systems. The benefit of a welded frame made from steel is more rigid (elastic modulus of mild steel is roughly 3x greater than most aluminum alloys [5]), steel has a greater fatigue resistance for applications that have repeated loading, and generally steel is less expensive than aluminum [6]. Some of the drawbacks to using welded steel frames are that they are not easily adjustable and require an individual or team of individuals who are skilled in welding to construct or add additional components. Tube and joint assemblies have similar benefits in modularity, but are often made from stainless steel, mild steel, aluminum, [7], [8], [9] or for many do-it-yourself (DIY) projects polymers such as polyvinyl chloride (PVC) are used. A major drawback of using a tube and joint system is it lacks the structural load carrying capabilities that T-slot or welded structures are capable of and the accessories or

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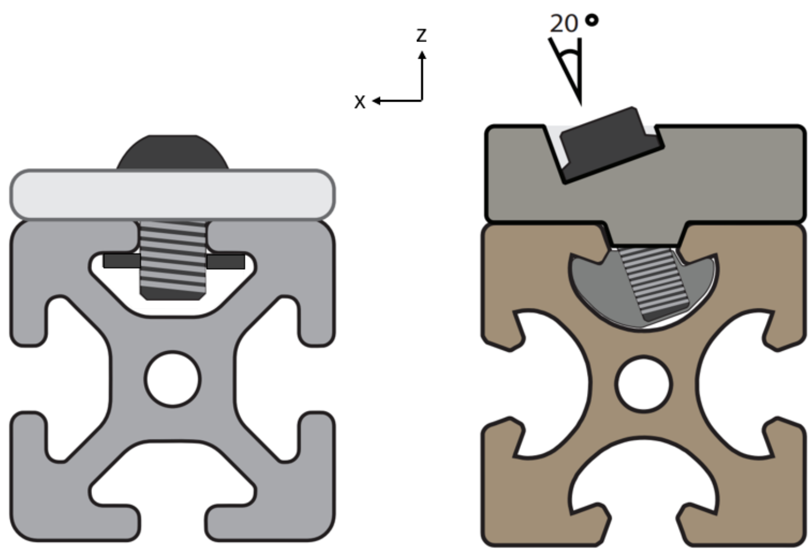
ability to add components to structures is not as easy as a slotted extruded aluminum structure.

The goal of this paper is to **prove that this novel cross-section geometry developed by AngleLock™ and corresponding connectors are able to support static loading conditions that common T-slot extruded aluminum framing cannot support.** This will be done by conducting a static analysis on a common T-slot extruded aluminum framing cross section and on the AngleLock™ cross section for static loading conditions in the *x*-, *y*-, and *z*-directions. Dynamic loading conditions will be discussed in a separate paper. Similarly, the mechanical properties and strength of materials analysis will be discussed in a separate paper as a continuation of this analysis.

Background

One of the most common issues of T-slot structures is that nuts and bolts for the connecting pieces slide inside the T-slot groove. This issue can be eliminated by making a small change in the cross-section of the profile. Figure 1 depicts a common T-slot cross section with corresponding connector and an AngleLock™ cross-section with corresponding connectors.

Common T-slot Cross-Section and Connecting Pieces | **Novel AngleLock™ Cross-Section and Connecting Pieces**



(a) (b)

Figure 1 Cross-section view of (a) common T-slot profile and connecting hardware (b) AngleLock™ profile and connecting hardware

Note the differences in the cross-section geometries and how the bolt for the AngleLock™ hardware is at a 20° angle. This is to align the bracket in the slot and to force the nut to interlock with the geometry of the cross section. This interlocking is a key part for why AngleLock™ components have more advantages compared to common T-slot components and will be discussed more in the analysis.

Static Analysis

This analysis will be done for a perpendicular corner bracket with corresponding hardware connected to a single four slot solid rail profile. Note that AngleLock™ does not have a flat nut and only has contoured slide-in nuts. Although common hardware for T-slots could be used on AngleLock™ profiles, it would not provide comparable stability due to the difference in cross-section geometries between common T-slot profiles and AngleLock™ profiles. Additionally, the use of non-AngleLock™ hardware on AngleLock™ profiles could damage the profile's cross section geometry. Since this analysis is only concerned with the connecting hardware, the shape or dimensions of the profile are inconsequential to the analysis.

An isometric view of the common T-slot and AngleLock™ assemblies with a perpendicular corner bracket is shown in Figure 2 along with the assumed loads and moments that will be used for this analysis.

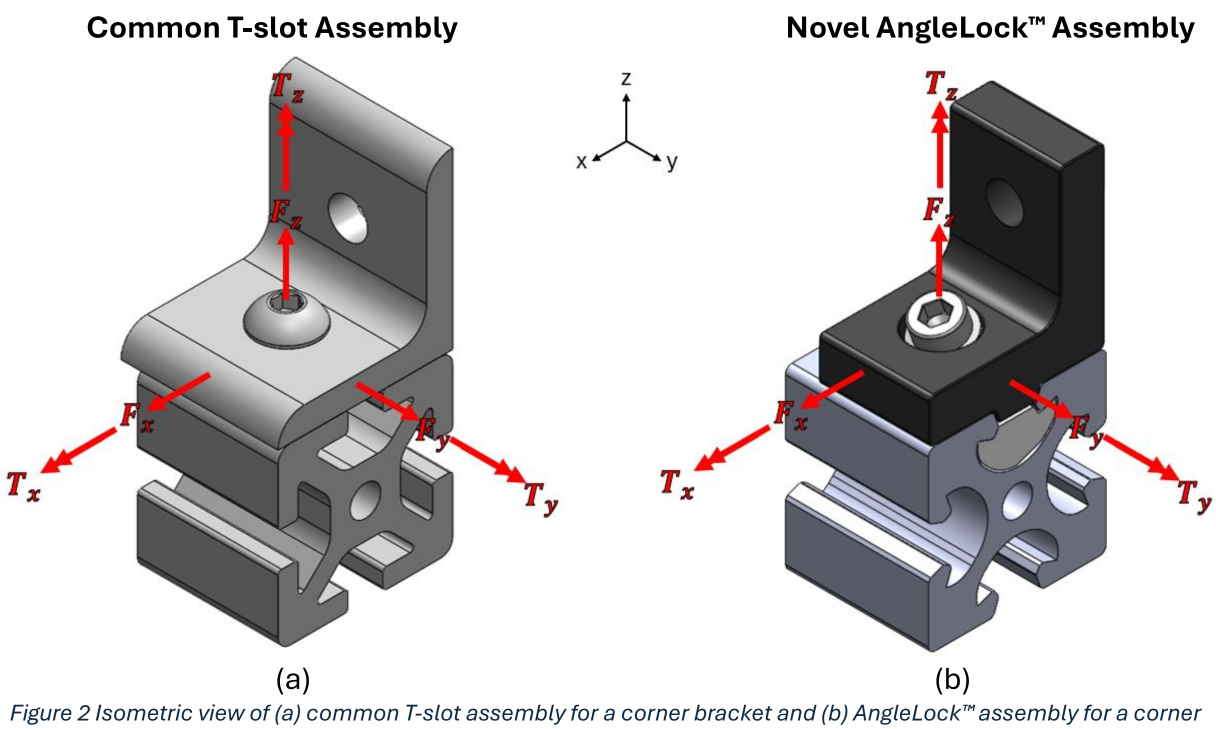


Figure 2 Isometric view of (a) common T-slot assembly for a corner bracket and (b) AngleLock™ assembly for a corner bracket

A static analysis can be done to show how each slotted aluminum extrusion opposes forces and torques applied to it. A similar analysis could be done for loading in the negative direction and would yield the same results. Figure 3a and Figure 3c show the friction planes (red arrows) that highlight where the components rely on friction to oppose forces in the out-of-plane direction (i.e., *y*-direction with this coordinate system). Note that for common T-slot geometries there will be some reliance on friction in the *x*-direction due to the clearances between the parts. This will be discussed later in this section. Figure 3b and Figure 3d show the reaction forces (green arrows) that are in the plane (i.e., *x*- and *z*-directions). Note that AngleLock™ have two different possible solutions to eliminate any dependencies on friction in the out-of-plane direction to make a fixed support that common T-slot structures do not offer. This will be discussed after the static analysis.

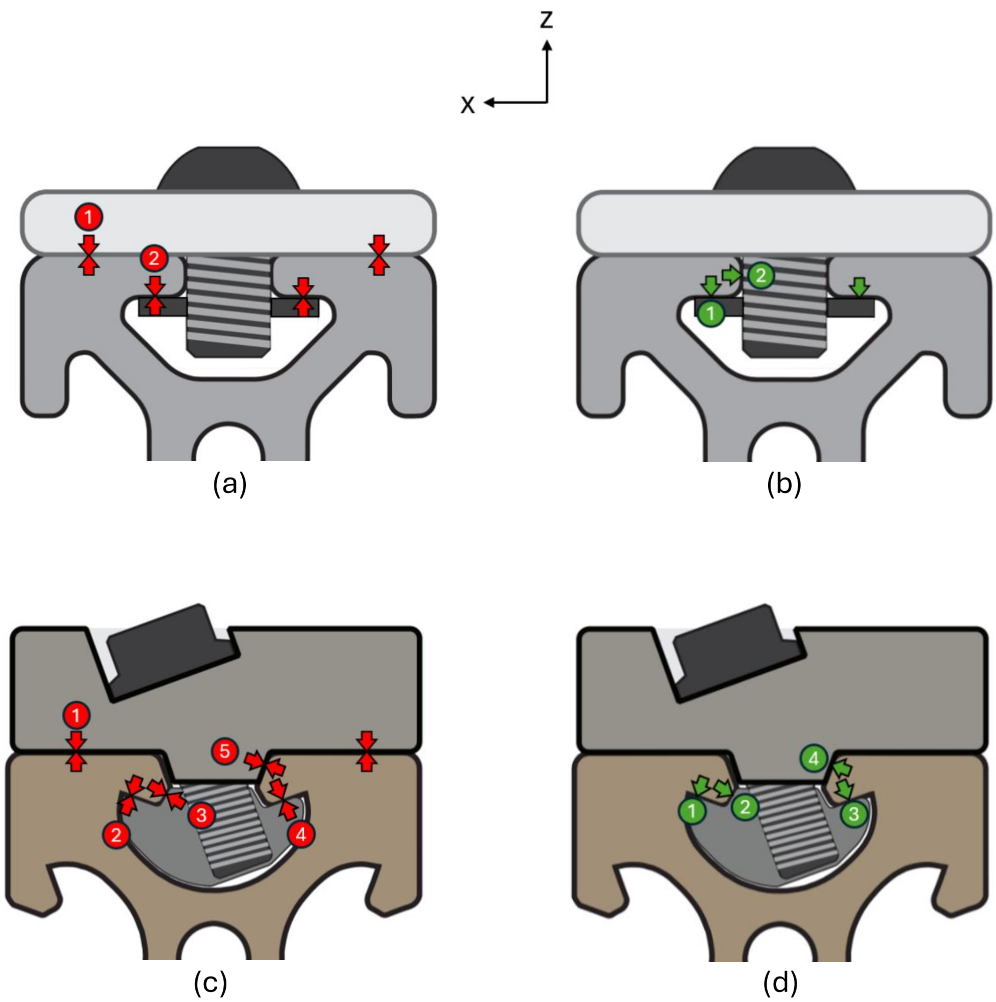


Figure 3 (a) reaction forces due to friction for loading in the positive out-of-plane, or y-direction for common T-slot (b) reactions to physical interactions for positive loadings in the x- and z-directions for common T-slot (c) reaction forces due to friction for loading in the positive out-of-plane, or y-direction for AngleLock™ (d) reactions to physical interactions for positive loadings in the x- and z-directions for AngleLock™

Note that for common T-slot components there is a small clearance between the bolt and the lobes of the cross-section. For example, a 40x40mm profile uses M8 bolts (i.e., 8mm nominal diameter bolts) to secure the connecting pieces or components. The true major diameter of a M8 bolt is about 0.1mm smaller than the reported nominal diameter (i.e., the true major outer diameter of a M8 bolt is around 7.9mm). The width of the slot between the lobes at the outermost parts of the cross section is about 8.25mm. This means that, if the bolt is in the absolute center of the slot, there is about a 0.175mm clearance on either side of the bolt. Therefore, common T-slot profiles have two separate loading directions that rely on friction to oppose forces. The clearance between the diameter of the bolt and the width of the slot between the two lobes is the limiting factor as the clearance between a single nut and width of the channel is roughly 2mm on each side.

It is obvious from Figure 3 that both structures will be able to oppose loading in the *z*-directions and torques about the *x*- and *y*- directions similarly for small loads. **Note that for larger loads, there is a significant difference between loading components of a T-slot and loading components of AngleLock™ components both in plane and out-of-plane shown in Figure 3.** Due to the clearances mentioned previously of the T-slot system, the assembly relies on friction in the *x*-direction before the bolt reaches one of the lobes of the profile to physically oppose loading in the *x*-direction. This means that the entire assembly for a common T-slot system can slide up to 0.35mm in the *x*-direction before coming into contact with one of the lobes. AngleLock™ components do not have this same limitation.

AngleLock™ components are self-aligning. When a bolt of an AngleLock™ assembly is tightened, the 20° angle forces the top bracket to engage with one side of the slot in the channel and the nut engages with the opposite side in the v-shaped section of the main channel as seen in Figure 3d. This means that every time an AngleLock™ component is attached to an AngleLock™ extrusion, the components will always be centered and it is repeatable. This repeatability in the self-alignment is paramount when dealing with larger assemblies with many connections and components as the propagation of error in common T-slot assemblies due to the aforementioned clearances can lead to assemblies with significant overall dimensional inaccuracies.

A significant difference between these two structures becomes obvious when looking at the sum of moment equation about the *z*-direction. Since the T-slot nut is flat, it can only resist a torsional load about the *z*-direction with a corresponding frictional force. Similarly, both the T-slot and AngleLock™ structures resist a force in the *y*-direction with a corresponding frictional force. AngleLock™ has a solution to eliminate the reliance on friction in the *y*-direction that is discussed later. Mentioned previously, a common T-slot assembly also relies on friction to oppose forces in the *x*-direction before meeting the edge of the lobe that applies an opposing physical force as seen in Figure 3c. When the static frictional force is overcome the component will move and the bolt will meet the lobe of the extrusion which supplies an opposing force.

Note that for this analysis there are some simplifications that are being made and assumptions that are explained during the analysis. These simplifications and assumptions are made because the goal of this analysis is not to find exact values for forces, but to show what the forces are and what contributes to them.

For a common T-slot geometry, the static analysis for the sum of the forces in the *x*-direction is

$$\Sigma \mathrm{F}_x = 0 \qquad (1)$$
$$\mathrm{F}_x = \begin{cases} \mu F_{Bolt} & \text{Inbetween lobes} \\ F_2 & \text{When bolt comes into contact with lobe} \end{cases}$$

where μ is the coefficient of friction between the nut and extrusion and is assumed to be the same between the bracket and the extrusion. It is likely that they are different, but is simplified for this analysis and combined into one term. For a common T-slot geometry, the static analysis for the sum of the forces in the *y*-direction is

$$\Sigma \mathrm{F}_y = 0 \qquad (2)$$
$$F_y = \mu F_{Bolt}$$

Again, the coefficient of friction between the nut and extrusion and is assumed to be the same between the bracket and the extrusion and is combined into one term to simply demonstrate that the reaction for a force in the *y*-direction relies on friction alone. For a common T-slot geometry, the static analysis for the sum of the moments about the *z*-axis is

$$\Sigma M_z = 0 \qquad (3)$$
$$T_z = \mu \frac{F_{Bolt}}{A} \int_A r(x,y) P(x,y)\, dA$$

where $\frac{F_{Bolt}}{A}$ is the pressure exerted on the friction planes shown in Figure 3a, $r(x,y)$ is a function that describes the distance from the center of rotation or the moment arm from the center of the bolt to the locations in contact with friction, and $P(x,y)$ is the perimeter of the area at any given moment arm, r. A similar term can be determined for the top of the slot where the bracket and extrusion are in contact, but is not found to simplify the analysis. Thus, only one term is shown to simply demonstrate the opposing torque solely relies on friction and takes the above form.

For the AngleLock™ geometry, the static analysis for the sum of the forces in the *x*-direction is

$$\Sigma \mathrm{F}_x = 0 \qquad (4)$$
$$F_x = R_2 \sin\theta_2 + R_3 \sin\theta_3$$

Note that there is no dependencies on friction for a force in the *x*-direction like there was for common T-slot structures. For the AngleLock™ geometry, the static analysis for the sum of the forces in the *y*-direction is

$$\Sigma \mathrm{F}_y = 0 \qquad (5)$$
$$F_y = \mu F_{Bolt}$$

Later in this section there is a discussion about how AngleLock™ can eliminate this dependency on friction. Again, to simplify the equation all 5 of the friction planes and points are combined into one term here. For the AngleLock™ geometry, the static analysis for the sum of the moments about the *z*-axis is

$$\Sigma M_z = 0 \qquad (6)$$
$$T_z = R_1 \sin\theta_1 + R_2 \sin\theta_2 + R_3 \sin\theta_3 + R_4 \sin\theta_4$$

Note that there is no frictional term combating a torque about the *z*-axis like there is for common T-slot profiles.

AngleLock™ has two unique solutions to prevent movement in the longitudinal, or *y*-direction, and become a zero-degree of freedom or fixed connection. One solution is to add a spacer (called a support profile) that is the same length as the distance between connections which has the same profile as the nut shown in this analysis. This support profile can supply a physical opposition to a force rather than simply relying on friction. AngleLock™ also has a self tapping threaded insert which goes into the channel. The limitation of this self tapping threaded insert is that it permanently deforms the channel where it is inserted.

Summary and Conclusion

From the static analysis it is clear that the cross-sectional geometry of the AngleLock™ profiles impacts structural integrity significantly by removing the reliance on friction that common T-slot framing has. The self aligning aspect of the AngleLock™ components allows for more precise design since the components will always be centered in the channel and also allows for more predictable assemblies. AngleLock™ also has two solutions to completely eliminate any reliance on friction and rendering the connection to become fixed in all directions.

This is a significant improvement over common T-slot structures and eliminates the issues of T-slot components shifting and moving over time. AngleLock™ assemblies do not move and shift due to the self aligning and interlocking aspect of the design. This leads to assemblies that are more reliable and require less maintenance since minor adjustments from components moving are unnecessary for AngleLock™ assemblies. The AngleLock™ profiles and connecting hardware can significantly improve reliability, eliminate maintenance time due to minor adjustments in connecting hardware, and can save money due to not having to service the connections periodically like in a common T-slot assembly. This can ultimately save time and money.

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