Chapter 5

SIMULATION OF TWELVE-SIDED REFLECTOR

5.1 Motivation

To evaluate the feasibility of the proposed ISA concept for larger structures, a twelve-sided polygonal ring structure with forty eight cable elements was selected as the baseline model (see Fig. 5.1). Using the simulation techniques outlined in Chapter 4, this study aims to explore the inherent challenges of assembling ring-like structures with a cable net interior. Key issues such as potential snags, misalignments, and the critical importance of the assembly sequence are analyzed. Additionally, the approach to prestressing the structure is analyzed to assess its effects on overall structural integrity and efficiency, offering insights into optimizing the ISA process for future large-scale applications.

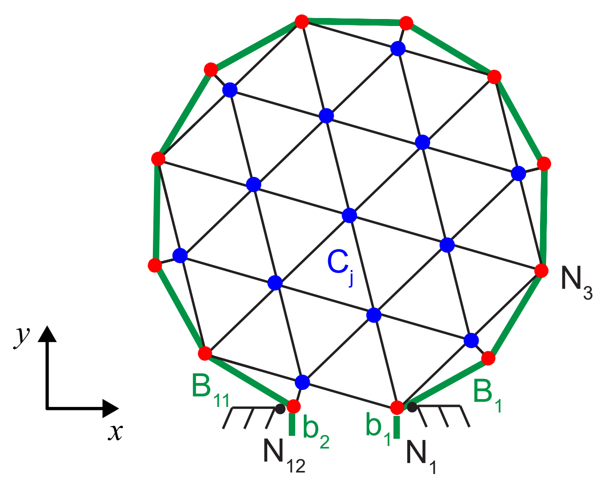

Figure 5.1: Geometry of twelve-sided reflector.

The dimensions and number of bays for the twelve-sided polygonal ring structure were chosen to match the 1.4-meter lab-scale prototype of the ISA concept currently under development, as described in Chapter 6. The original cable net configuration designed for D = 1.4 m, using the generalized design method detailed in Chapter 2 was simplified while adhering to the constraints specified in Section 4.2.2. This approach ensures that the simulation accurately reflects the prestress requirements of the design and remains consistent with the characteristics of the prototype, allowing for a meaningful comparison and assessment of the proposed ISA concept.

5.2 Effect of Assembly Plate Orientation

While the orientation of the assembly plate did not impact the final shape for the six-sided structure, this finding does not hold for larger structures. An intuitive observation is that orienting the assembly plate at the supplementary angle to the interior angle of each i-sided intermediate polygon during assembly, $\theta_{cr,\,i}$, could help avoid distortions or bias in the shape of the ring (see Fig. 5.2). This approach would ensure that the structure naturally forms the correct polygonal shape upon release of the final bay. However, this approach would also require adjusting the plate orientation at each B_i push-out step, increasing process complexity. Therefore the identification of a single effective orientation for the entire assembly is necessary.

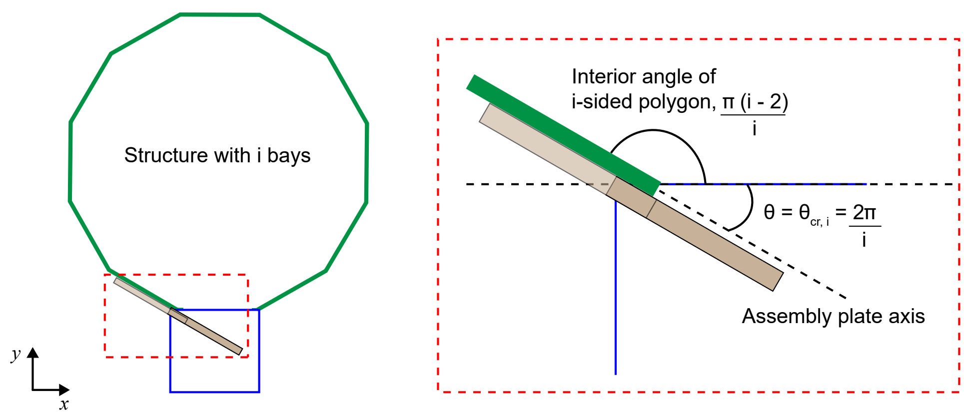

Figure 5.2: Relationship between critical assembly plate orientation, θ_{cr} and interior angle of perimeter truss.

Numerical simulations were conducted using three distinct assembly plate orientations: $\theta = 90°$, $60°$, and $30°$. These angles represent different scenarios: $\theta = 90°$ where the assembly plate is moved perpendicular to the truss support axis, $\theta = 30°$ corresponding to θ_{cr} for a twelve-sided polygon, and $\theta = 60°$, a midpoint between the two. Figure 5.3 shows 11 snapshots of the intermediate shapes during assembly.

For $\theta = 90°$, the shape of the structure is consistently biased to the right as bays are added (see Fig. 5.3(a)), due to the constraint imposed on the left side by the assembly plate. This results in excessive tension on the final set of cables, ultimately jamming the process and preventing the structure from achieving the intended dodecagonal shape upon release of the last bay. In contrast, for $\theta = 30°$, the intermediate polygons are flatter and a clear leftward bias can be seen, with the final set of bays aligning closely to the desired shape (see Fig. 5.3(c)), as anticipated for $\theta = \theta_{cr,\,12}$. However, this configuration still introduces distortions in the first half of the ring structure, i.e., in bays B_1 to B_5.

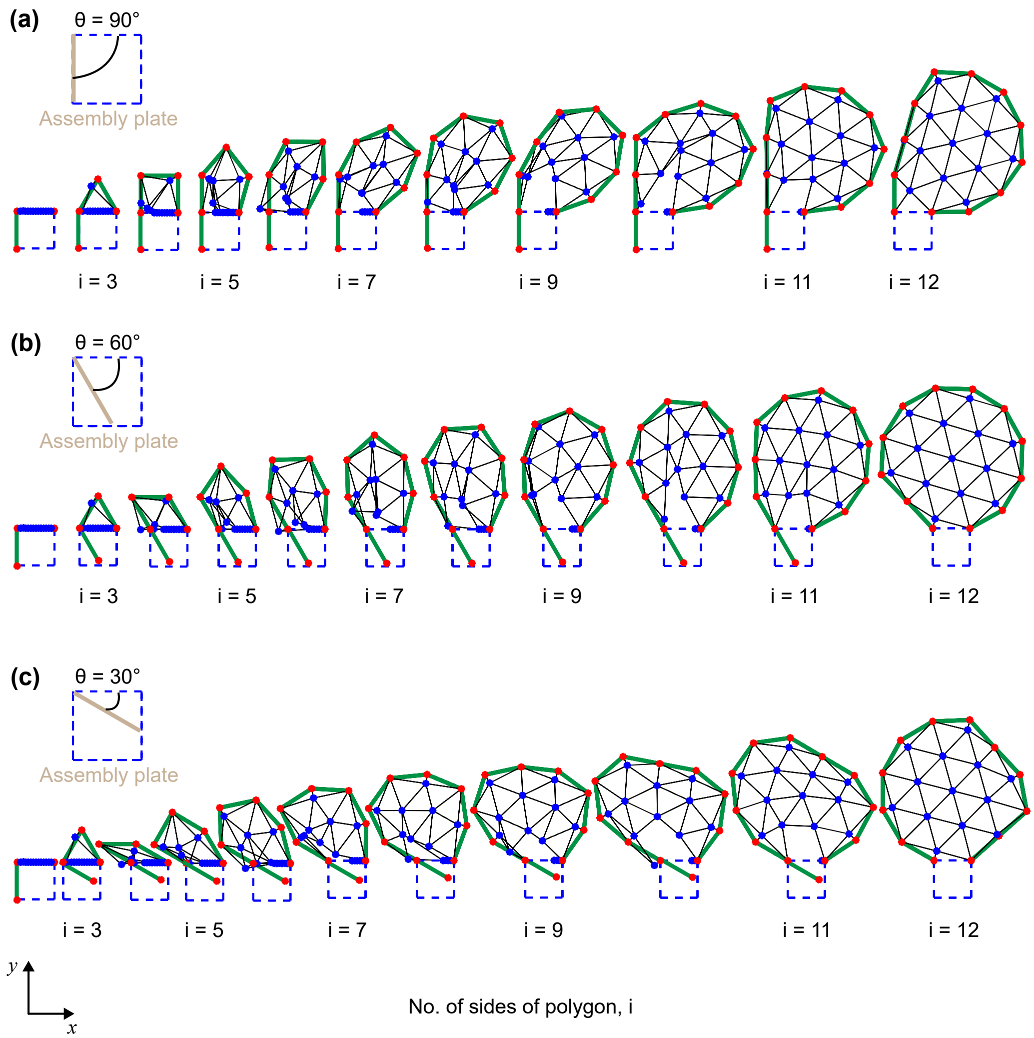

Figure 5.3: Effect of assembly plate orientation: (a) $\theta = 90°$, (b) $\theta = 60°$, and (c) $\theta = 30°$.

The intermediate case $\theta = 60°$, produced the most balanced result (see Fig. 5.3(b)), achieving a configuration that is closest to the target polygonal shape while maintaining relatively symmetric deployment throughout the assembly process. Although determining an angle that achieves the final desired shape while maintaining symmetric intermediate shapes is not straightforward, these results demonstrate that the proposed ISA concept is highly sensitive to the assembly plate orientation. Further optimization of the angle will be important to ensure both precision and efficiency in larger-scale deployments.

5.3 Effect of Prestressing Method

The proposed ISA concept depends on releasing the final bay of the ring to trigger the formation of the desired final configuration and to apply prestress to the structure. However, as discussed in Chapter 4 and Section 5.2, some cables may become excessively tensioned, which can disrupt the remaining assembly process. To address this issue, alternative methods for applying prestress at various stages of assembly were investigated.

A novel approach was developed, yielding promising experimental results with the lab-scale prototype by successfully achieving the intended final shape and effectively prestressing the structure. This method of prestressing is as follows (see Fig. 5.4): after deploying the first two pre-built bays (B_1 and B_2), the edge cable $C_{edge,3}$ is connected to node N_3, and the assembly plate is retracted. At this point, truss support S_1 is moved closer to the assembly plate along the truss support axis. The remaining bays are then assembled and released while S_1 stays stationary in this position, and this is key to ensuring that the cables remain slack during assembly, thereby preventing any disruptions to the assembly process. Once the final bay (B_{m-1}) is released, prestressing is carried out by moving S_1 back to its original position. This has the effect of stretching the cable net and applying the necessary tension to the structure.

It is important to emphasize that initiating the prestressing process of the structure requires the movement of a component at the final stage of assembly. In the original concept, this component was the final bay, whereas in the modified concept, it is the truss support S_1. Regardless of the approach, effective prestressing of the structure can only be achieved if the cables are also sufficiently tensioned by the end of assembly. Essentially, cables must fulfill conflicting requirements at different stages of assembly: they need to remain slack during the assembly process to ensure smooth progression, but they must be tensioned at the end to achieve the correct shape and structural stiffness.

As detailed in Section 4.2.2, the simulation setup is such that cables are intentionally modeled to be nearly slack at the end of assembly, with $u \approx 0$, meaning the final shape is not prestressed. Modifying the prestressing method—from moving the last bay to moving the truss support—only allows the cables to remain slack during assembly, facilitating a smoother assembly process and helping the structure approach the desired final shape more effectively. The process of attaining final prestress will be further examined in Section 5.5.3.

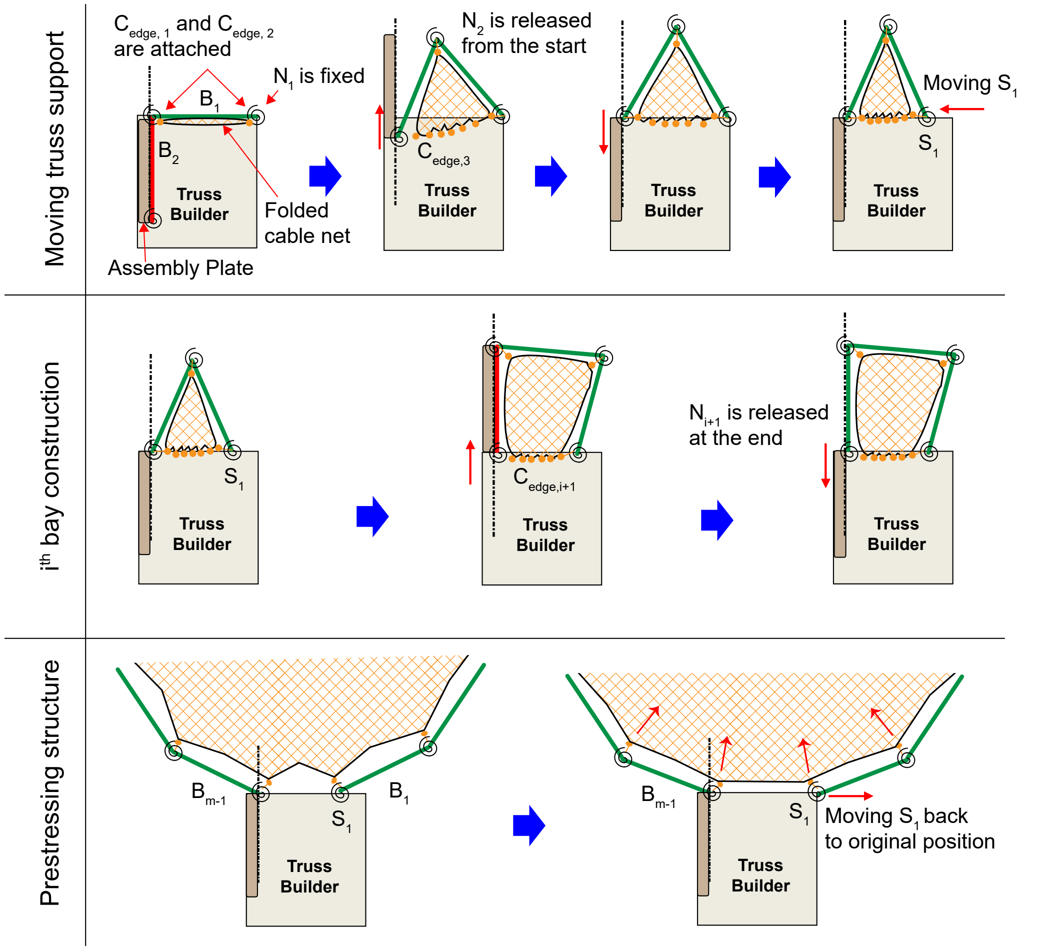

Figure 5.4: Two-dimensional view of the modified prestressing method: moving truss support, i^{th} bay assembly and prestressing the structure.

Figure 5.5 shows the simulation results for both methods of prestressing, with the assembly plate set at $\theta = 60°$. The deployment of the ring for the moving truss support case (see Fig. 5.5(b)), remains relatively symmetric and similar to the case of the moving last bay (see Fig. 5.5(a)), though the former is stretched along the y-direction due to the truss supports being positioned closer together. After releasing the last bay, the polygonal shape for the moving truss support case closely approximates the final shape achieved with the moving last bay case (see $i = 12$ in Fig. 5.5(a)). However, the final adjustment of resetting the truss support triggers the formation of precise polygonal shape of the truss, transforming the assembly from its preliminary state into the desired configuration, as shown in Fig. 5.5(b). This outcome confirms the effectiveness of the modification and underscores the critical importance of considering not only the effect of the assembly plate orientation but also the prestressing method in achieving the desired final shape.

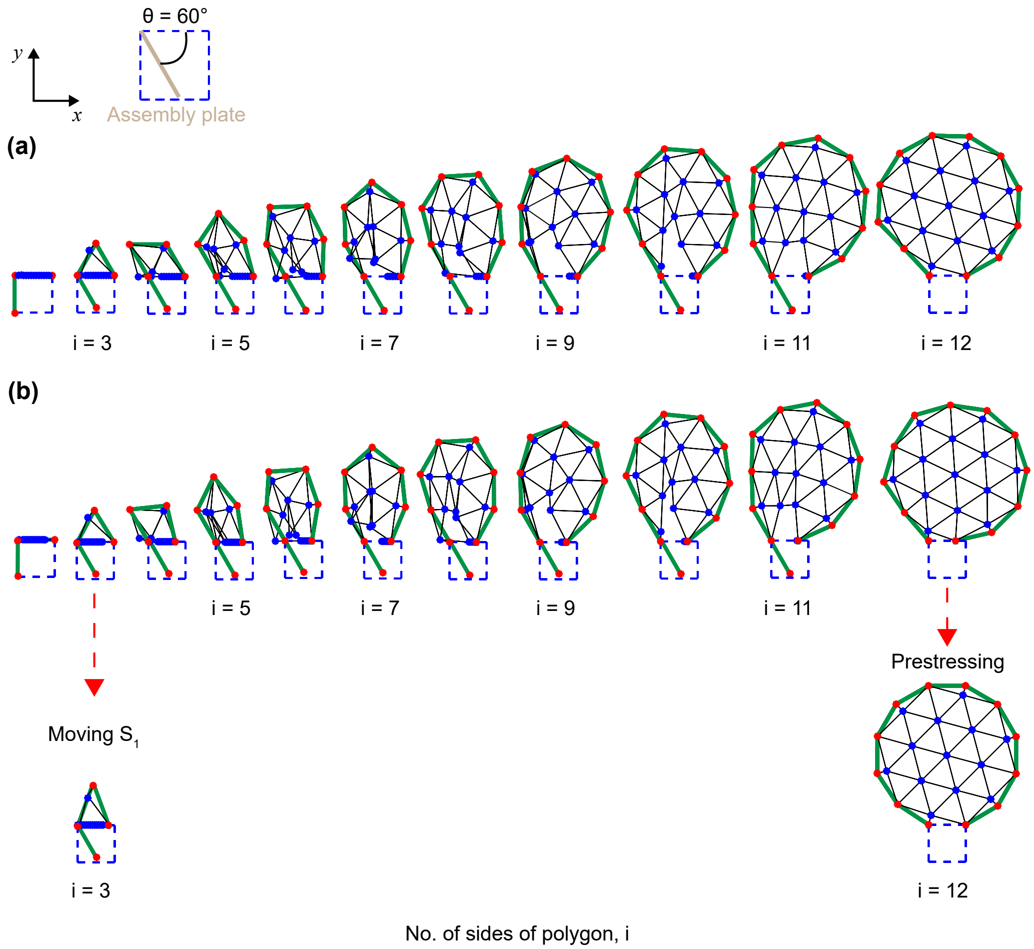

Figure 5.5: Effect of the prestressing method: $\theta = 60°$, (a) moving last bay: S_1 is fixed (b) moving truss support: S_1 is moved by 0.1 m at the start and reset at the end of assembly.

5.4 Effect of Cable Net Orientation

The ISA concept replaces one of the bays with the truss builder, that supports the structure during and after assembly. While the six-sided structure's cable net remains symmetric relative to the truss support, regardless of the chosen bay, the twelve-sided structure does not share this symmetry (see Figs. 4.7 and 5.1), indicating that there are two options for placing the truss builder, as illustrated in Fig. 5.6. Hence there are two possible orientations for the cable net relative to the truss builder. A comparison of these orientations highlights a significant difference: orientation 2 includes a cable element connecting node N_{12} to node N_{10}, while orientation 1 does not. This difference is significant, particularly when relying on the release of the last bay B_{m-1} to trigger the final polygon formation, prestressing the structure. In orientation 1, it may be more difficult to achieve the desired shape near node N_{11}.

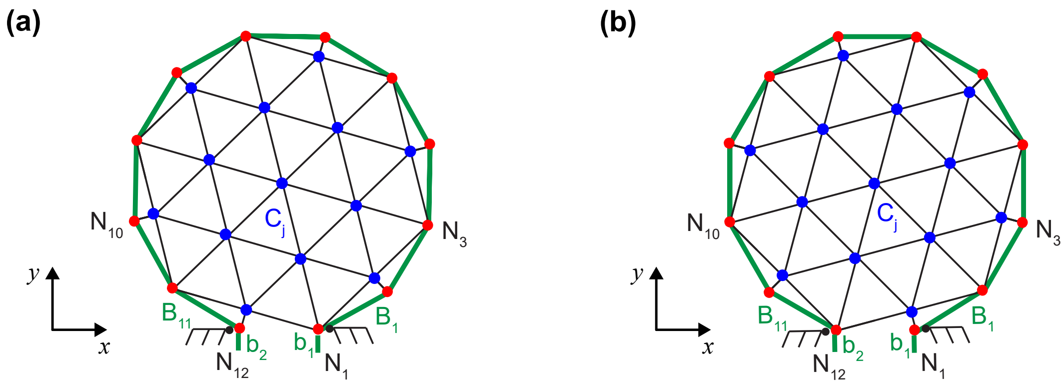

Figure 5.6: Two configurations of the cable net: (a) orientation 1 (b) orientation 2.

Figure 5.7 illustrates this with simulation results for both orientations, prestressing the structure by moving the last bay and at an assembly plate angle of $\theta = 60°$. The final configurations are mirror images, with key differences during assembly emphasizing the importance of the cable net configuration near the nodes. In orientation 1, the last two bays are collinear at nodes N_{10} through N_{12} as expected, while in orientation 2, the first two bays are collinear at nodes N_1 through N_3.

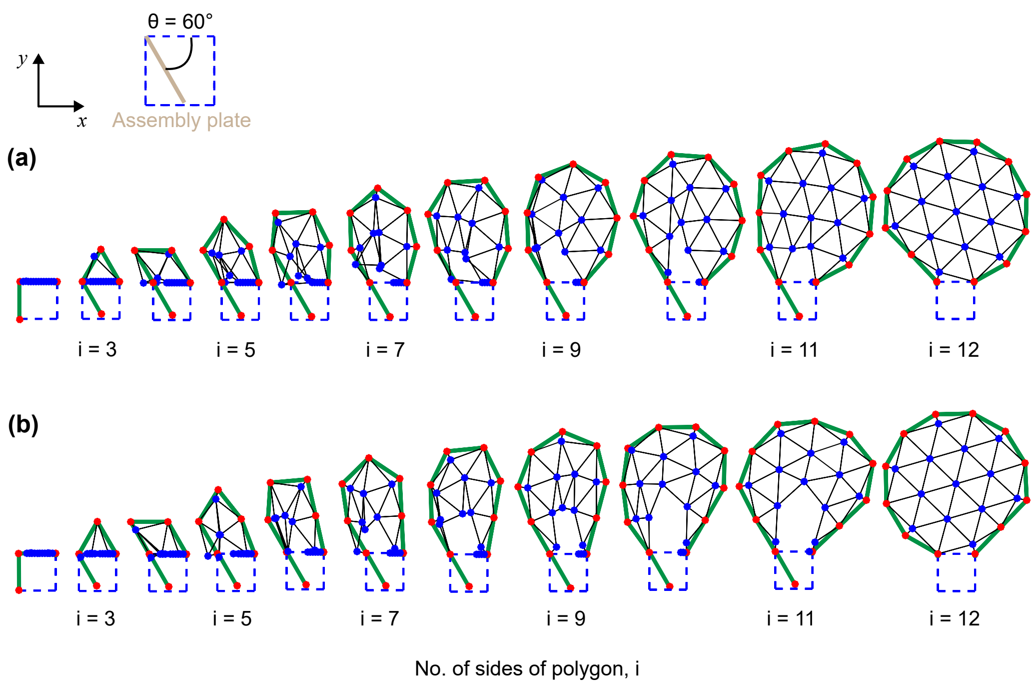

Figure 5.7: Effect of cable net orientation relative to the truss support: prestressing by moving last bay and at $\theta = 60°$, (a) orientation 1 (b) orientation 2.

Examining the final configurations for the case of prestressing the structure by moving the truss support (see Fig. 5.8) shows that both orientations achieve the desired polygonal shape for this method of prestressing. A comparison of truss shapes before prestressing shows similar differences between the two orientations as observed when moving the last bay. This suggests that it is indeed this final step that enables the structure to achieve the desired configuration, regardless of the cable net orientation. Thus, the orientation of the cable net is considered more critical when prestressing relies on the movement of the last bay.

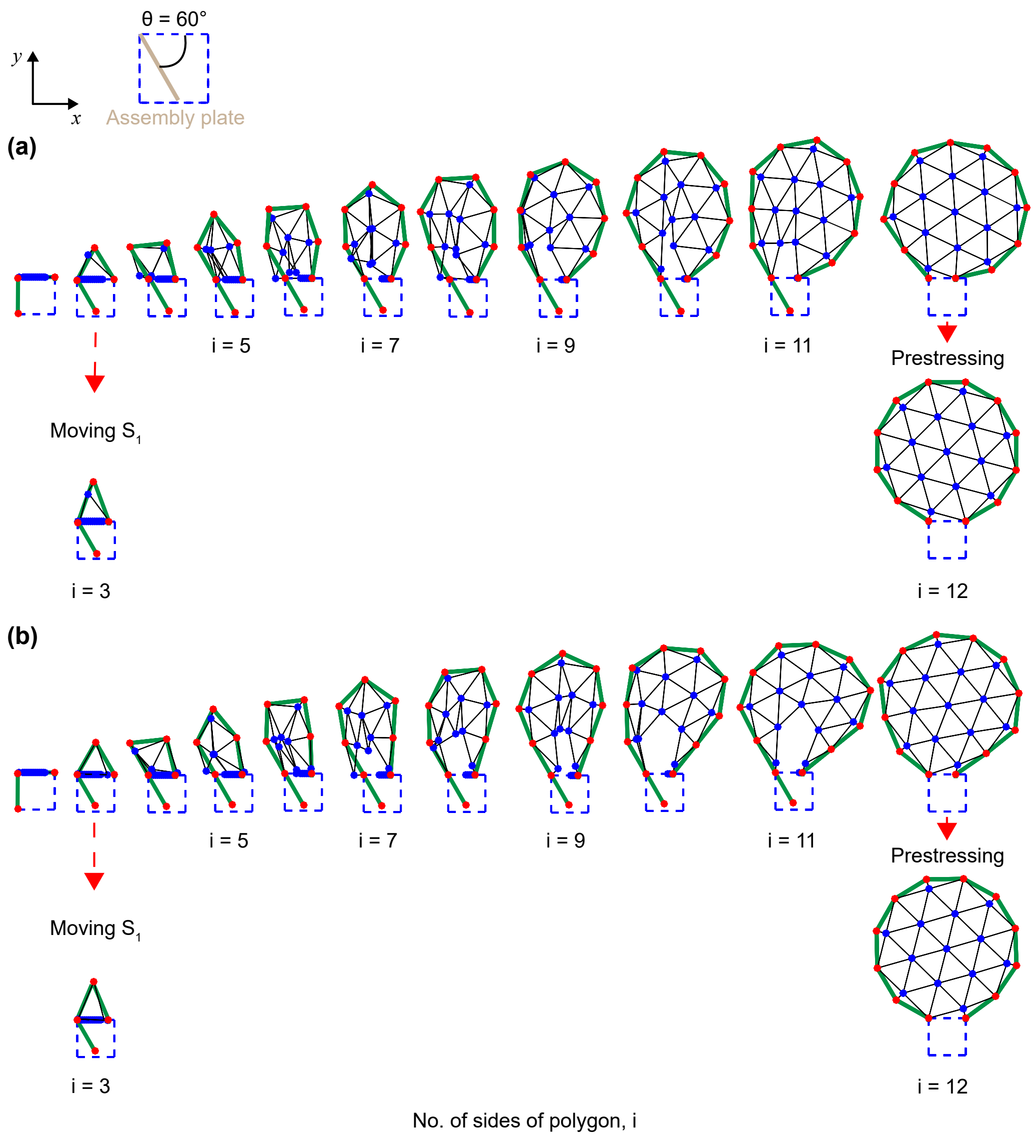

Figure 5.8: Effect of cable net orientation relative to the truss support: prestressing by moving truss support and at $\theta = 60°$, (a) orientation 1 (b) orientation 2.

5.5 Further Considerations for Assembly Simulation

5.5.1 'Jamming' Condition

In some instances, nodes became 'jammed' during assembly disrupting the process. This led to the conjecture that this occurs when the active cables and the truss form a "tensegrity" structure that self-locked and could not move. This issue was resolved by introducing a disturbance into the structure, by applying small displacements to affected truss nodes, which allowed the assembly to proceed as intended. For example, Figure 5.9 shows a case where the assembly became jammed during the activation of cables connected to node N_{10} indicated by black dotted lines). Moving node N_9, as indicated by the red arrows (see Fig. 5.9(a)), prior to the cable activation step allowed the cable activation step and therefore the overall simulation to continue till completion, and obtain the final configuration indicated in Fig. 5.7(b).

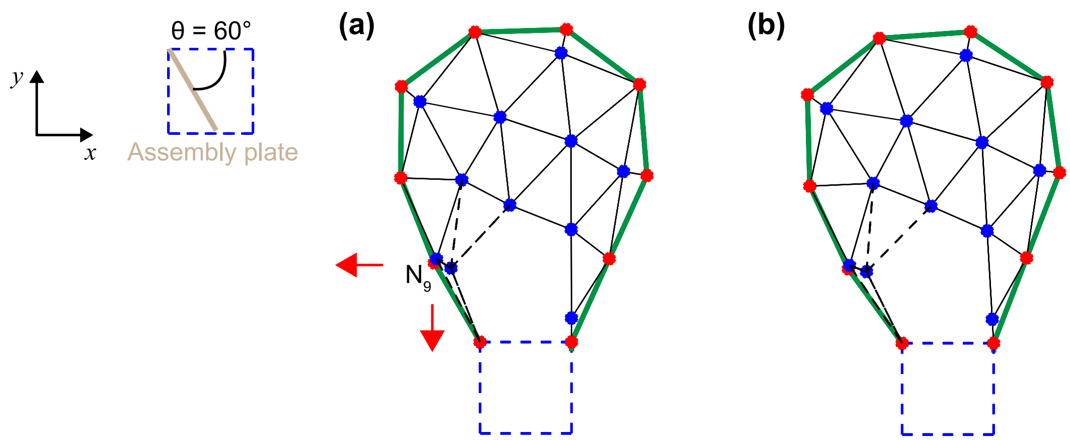

Figure 5.9: 'Jamming' condition for $\theta = 60°$, orientation 2 and prestressing by moving last bay: (a) 'jammed' configuration, and (b) resolved configuration.

5.5.2 Cable Activation and Bay Release Sequence

It was also observed that the sequence of steps towards the end of the assembly—specifically the order of 'cable activation' and 'bay release'—had a significant impact on the process. This is caused by large tensions in the cables that develop due to the constrained position of the last bay on the assembly plate, which in turn disrupts the assembly. Specifically for the $\theta = 60°$ case, releasing bay B_{11} before activating the cables connected to node N_{12} enabled the assembly to be completed successfully and achieve the desired final shape. This adjustment was effective even when moving the last bay for prestressing, demonstrating the critical role of step sequencing in overcoming tension-related issues and ensuring successful assembly.

5.5.3 Prestressing at the Final Assembly Stage

Referring to the case shown in Fig. 5.3(b), although the simulation did not 'jam,' the final shape is not fully correct, because node N_{11} is collinear with nodes N_{10} and N_{12}. Upon examining the corresponding graph that tracks the evolution of cable extensions, particularly during the last stage of the assembly (see the insert in Fig. 5.10(a)), it is evident that some cables have become slack, which likely explains the deviation in the final configuration.

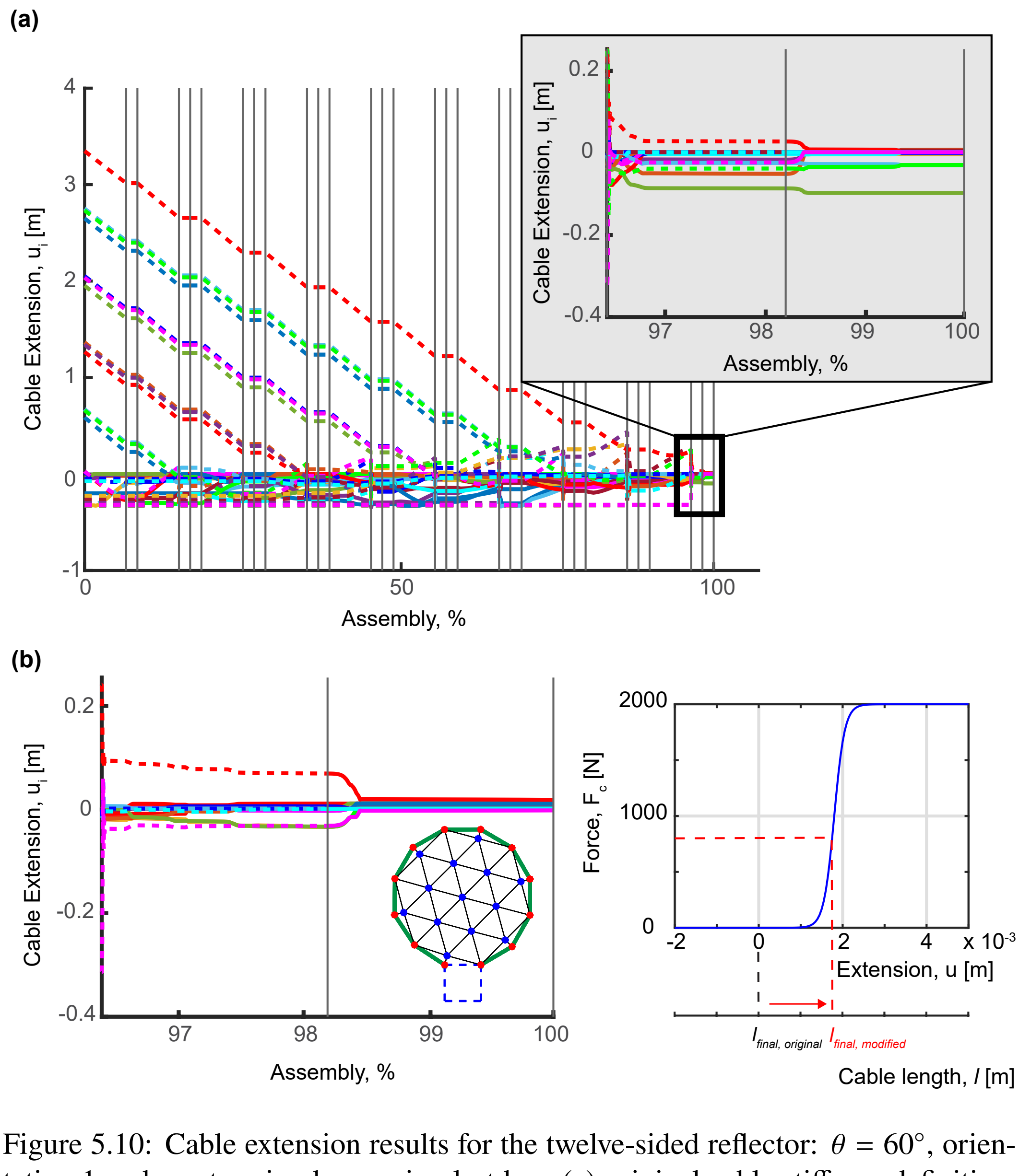

Figure 5.10: Cable extension results for the twelve-sided reflector: $\theta = 60°$, orientation 1 and prestressing by moving last bay, (a) original cable stiffness definition, and (b) modified cable stiffness definition to reflect prestress.

According to the cable stiffness definition discussed in Section 4.2.2, the cables were initially designed to be unstressed at the end of assembly (i.e., at $u \approx 0; F_c \approx 0$) to allow for smooth continuation of the assembly process. However, if the stiffness is redefined by adjusting the final length of the cable so that cables are prestressed at the end of assembly (i.e., at $u \approx 0; F_c \neq 0$), the cables will have to remain under tension as intended, ensuring the correct shape is achieved. This is demonstrated in Fig. 5.10(b), where the modified cable stiffness leads to the desired final configuration, as shown in the inset.

In summary, the successful completion of the ring-like structure in the simulation, along with its effective prestressing, relies on both the prestressing method and the cable stiffness model used. The chosen prestressing approach ensures uninterrupted assembly (see Fig. 5.5), while the stiffness model is crucial for reflecting the actual prestress at the end. Maintaining cable tension with an appropriate stiffness model enables the structure to achieve the desired configuration and stability.

5.6 Chapter Conclusions

This chapter has addressed, through simulations, the major challenges of assembling and prestressing large polygonal-ring structures using the proposed ISA concept. These difficulties are compounded by the challenge of accurately representing real-world conditions in simulations. However, it is essential to interpret the simulations carefully, as robust simulations become increasingly important for predicting intermediate assembly shapes and ensuring continuity as the structure scales, given that full-scale models are impractical for optimizing ISA concepts.

Simulations of a twelve-sided polygonal ring revealed that the assembly plate orientation and prestressing method are critical in ensuring successful assembly and achieving the final desired configuration. Specifically, an assembly plate angle of $\theta = 60^\circ$ offered the best balance, avoiding excessive distortions during intermediate stages. That said, the simulations suggest there may be multiple angles for successful assembly, indicating a solution space rather than a single, unique solution.

The key to the success of the ISA concept is the method of prestressing, whether by releasing the final bay or adjusting the truss support position. Both methods, albeit novel, were shown to be effective, provided the cables are sufficiently tensioned at the end of assembly. Additionally, ensuring smooth progression through assembly required careful sequencing of steps, particularly during the final stages where premature cable tension could cause disruptions.

The numerical simulations have demonstrated the importance of a carefully-defined cable stiffness model, where the correct application of tension ensures that the final structure forms the desired polygonal shape per original design. Adjusting the stiffness model to reflect actual prestress at the end of assembly played a crucial role in maintaining the required structural integrity. Overall, this simulation study captures key design features and provides a fundamental understanding of how different assembly sequences, assembly plate orientations, and cable net configurations affect the process. It also underscores the need for further optimization of the assembly parameters, including plate orientation and prestressing techniques, to achieve precision and efficiency in future large-scale ISA applications.