Glazing system in the Kinetic Woolbeding Glasshouse

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Abstract

Designed by Heatherwick Studio, this new kinetic Glasshouse features 10 structural "Sepals" 15 m long that open and close on the Woolbeding Gardens (West Sussex, England). Bellapart participated in the geometric, structural and automation design and engineering from early stages and did its detailing, fabrication and site assembly.

In its closed position, the Glasshouse is a 14.5 m high building with a 15 m diameter base and a maximum diameter of 19 m at the base of its 'kinetic' roof, at 2.8 m from the ground level. Its ten-sided façade is fully cladded with Isolating Glass Units (IGU's), while the main structure is made of tapered welded reconstituted profiles of mild steel that meet in sharp angles and complex nodes. To allow its movement, the Glasshouse relies on 10 hydraulic cylinders. When closed, a pneumatic system inflates a gasket system to achieve a weathertight building envelope.

In this paper, especial attention is given to the IGU's. They are mostly irregular quadrilaterals whose sustain strategy inside a RAICO® system required a detailed study, especially for the moving Sepals. Additionally, the Heatherwick's vision of a light-looking Sepal required the inclusion of a slender reinforcing profile in-between the Sepal IGU's. The profile was fatigue loaded and attached by means of structural silicone to the IGU's.

Keywords
Glasshouse, IGU, Structural Silicone, Fatigue, Kinetic Structure, Mobile Structure, Steel Structure, Hydraulic System, Pneumatic System

1 Glasshouse description

The Glasshouse is a hybrid between a building and a machine. Designed by Heatherwick Studio it is set as a folly in the middle of the Woolbeding Gardens (West Sussex, England), in a specially landscaped area. It will exhibit plants from the key zones of Silk Route and serve as an attraction point for the whole area. Bellapart participated in its design and engineering from early stages in the form of a PCSA and did the final development for the fabrication and site assembly.

1.1 Geometry

Two different parts of the Glasshouse may be distinguished: a Fix Base and ten moving Sepals with two main positons, closed and open (Figure 1).

At the ground level, the fix base is a 20-sided star polygon (bottom ring), nearly regular, with a diameter of around 15 m, then, at the top, at 2.8 m from the ground level, it transforms into another 20-sided star polygon (top ring) but this time with 10 of the sides being about 3 times longer than the other 10 and with a diameter of around 19 m (see Figure 2).

Figure 1. View of the Glasshouse. A. Closed position. B. Open position (© Heatherwick Studio)

Three different mild steel bespoke edgy tubes connect the bottom ring with the top ring, bracing the long sides except for the one where the entrance is located.

The Sepals are a 15 m long triangular pyramid with one side being much shorter than the other two. Their mild steel profiles are also bespoke edgy tubes, but are tapered to increase the lightness of the structure. In the closed position, the top node is 14.5 m high from the ground level. For its sustain, when closed, each Sepal relies on two hinges on the outer part (Figure 8) and two steel bearings in the inner part. When open, it is supported again by the two hinges and this time also by the hydraulic cylinder (see section 2) which also, when closed, avoids the Sepals from opening under wind suction loads.

1.2. Mechanisms description
The Woolbeding Glasshouse is actuated by 10 hydraulic cylinders (one cylinder for each Sepal) powered by a hydraulic power unit located in a plant-room 60 m from the Glasshouse, all connected by a weld-less stainless steel piping system (Figure 3)

Each hydraulic cylinder has a 230/140 mm diameter with a retracted length of 4280 mm and a stroke of 2840 mm, resulting on an extended length of 7120 mm with a maximum pushing force of 1039 kN. All the cylinders are fitted with proportional valves and position transmitters allowing closed-loop control and providing the synchronized movement with constant rotational speed required by the architectural specifications, with an opening and closing times of 4 minutes.

The Hydraulic Power Unit (HPU) provides hydraulic power to all the hydraulic cylinders using 255 kW electrical motors with fix displacement helical pumps attached, equipped with closed-loop pressure control to maintain the system working pressure at 190 bar.

The control system was designed to be operated by unexperienced users with little training, with special attention given to the functional safety system, which is able to identify, react and recover from the different failure modes with minimal operator intervention using a variety of failsafe devices across the different areas of the project.

Because of all this systems, the building was treated as a machine and was issued a EU Declaration of Conformity on completion which states the conformity with [1]-[4].

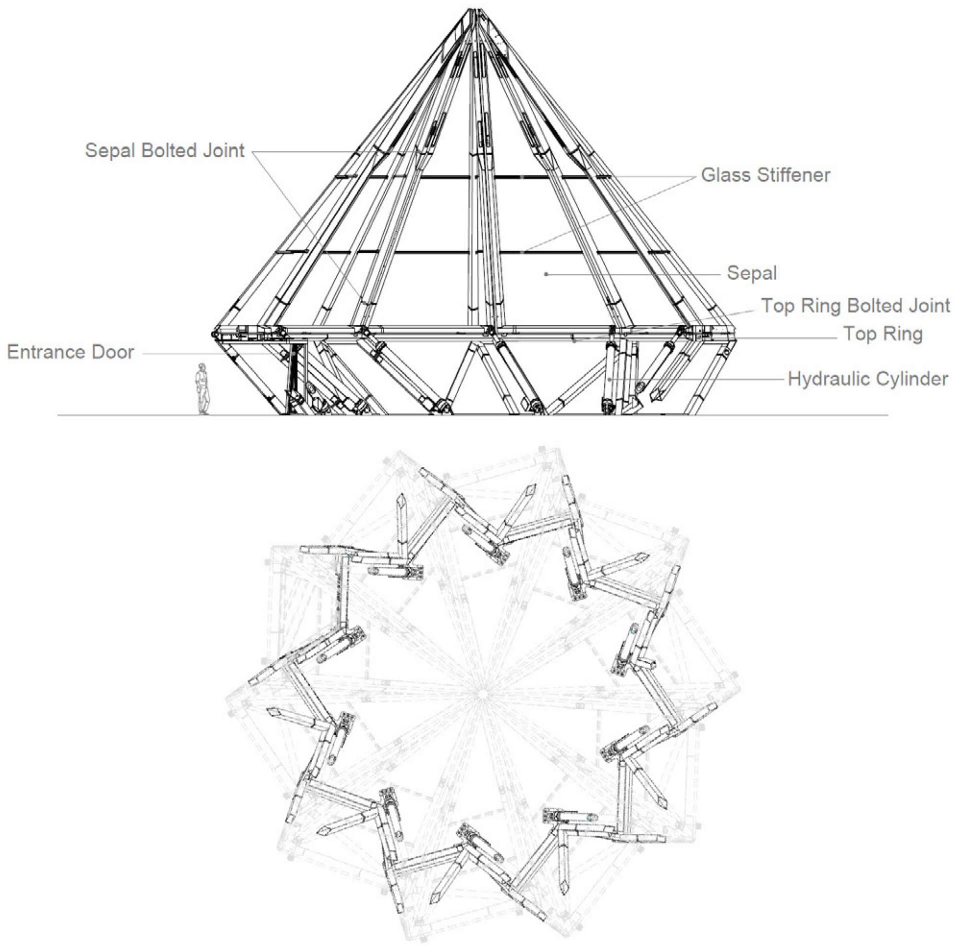

Figure 2. Section and plan view of the Glasshouse steel structure.

Figure 3. Hydraulic cylinders.

1.3. Weathertightness strategy
The technical requirements for the building require an airtightness strategy that allows no more than 3 air changes per hour as well as complete watertightness. The airtightness was verified by an on-site test once the building was completed. The watertightness was verified by a workshop test on the mock up.

In order to meet these weathertightness requirements all the gaps between Sepals and between Sepals and fix structure have to be sealed once the Glasshouse is completely closed. The selected solution had to completely close the perpendicular distances between faces, allowing for installation tolerances of 100 ±15 mm.

A pneumatic inflatable gasket system was chosen as the main sealing solution. A total of 25. inflatable gaskets are installed in the building, distributed as follows:

- 5 on top of the fix base, sealing against the base of the Sepals (Figure 4 A).
- 2 on each Sepal (one gasket per side of the Sepal) sealing against the gaskets of the adjacent Sepals.

All the gaskets are automatically inflated when the Glasshouse is completely closed and automatically deflated before opening. All the pneumatic machinery is located in the plant-room and the pressurized air is fed to the Glasshouse using an airline running along the hydraulic piping system.

In order to close the top opening of the Glasshouse, 10 bespoke EPDM foams were fabricated from on-site measurements and installed on the tip of each Sepal (Figure 4 B).

2. Main structure verification

In order to achieve a robust control of the loading and behaviour in all scenarios and positons (including the intermediate positons and accidental scenarios), the main structure verification was based in 8 different FEM models of the whole building (Figure 5) and 7 different FEM models of one single Sepal. The models were carried out with RFEM [5] and included the cylinder stiffness in the different positions using the formulation defined in [6].

This models were used to verify the deflection of the structure according to the limits in [7], the resistance and stability of the members according to [8] as well as the fatigue resistance according to [9].

From this models the forces for the detail verification were obtained (Figure 6). This verification was carried out with ANSYS [10], since the edgy and complicate geometry of the nodes made it necessary for the fatigue assessment. The detail verification included the resistance according to the annex C of [11] and the fatigue assessment, using the detail categories found on [9] and the recommendations on the Hotspot analysis found on [12].

The design number of cycles for the fatigue assessment was 50,000 over 60 years which corresponds to over 800 per year. Rather than thinking in over 2 operations per day, this number of cycles is taking in account an intensive usage during the warm months (about 10 cycles per day during the summer weekends). The Glasshouse is expected to remain in closed positon about 6 months a year.

Figure 4. Weathertightness. A. Inflatable gasket on top of the fix base. B. EPDM foam on top of a Sepal.

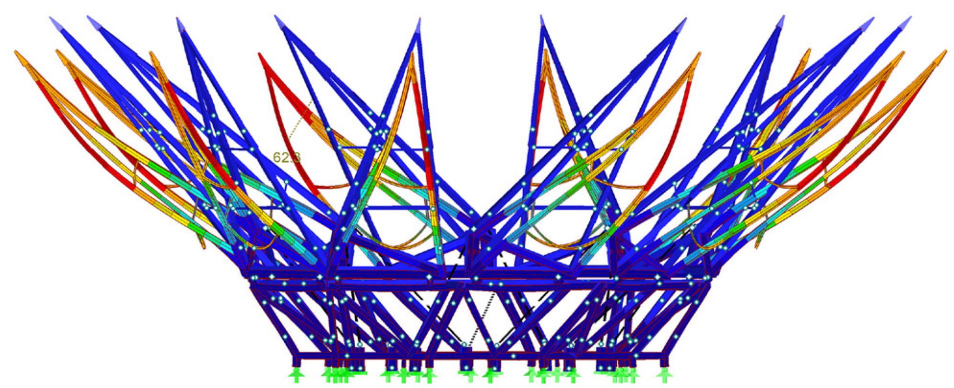

Figure 5. Global FEM model in open position, deformation under Dead Loads.

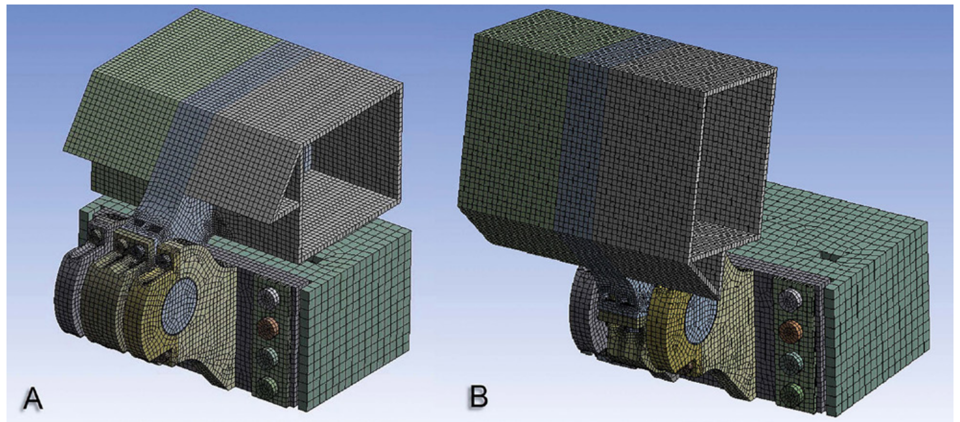

Figure 6. Local FEM model of the hinge. A. Closed positon. B. Open position.

3. Glazing

3.1 IGU's
The IGU's that clad the Glasshouse are mostly irregular triangles and quadrilaterals (Figure 7) being the bigger one around 3250x4600 mm. They have one gas chamber with 90 % Argon and 16 mm thickness and two double laminated glass packages. The interlayer for the laminated glass is made out of SGP® from Kuraray® and all of the glasses are Heat Strengthened (HS). Both packages are laminated and HS because both must have post-breakage stability since there is an inversion of their relative positon when the Sepals are open.

The exact composition is:

- Front Sepal IGU's: 10.10 HS 1.52 SGP + 16 90 % Argon + 8.8 HS 1.52 SGP®
- Rest of the IGU's: 6.6 HS 1.52 SGP + 16 90 % Argon + 5.5 HS 1.52 SGP®

A mild steel glass stiffener was included in the design to avoid an excessive deformation out of the plane of the insulating glass edge, which limit according to [13] is the lesser of L/175 or 15 mm.

The IGU's were verified by means of several FEM models representing the bigger ones of each type using the software SJ-MEPLA® [14] and according to the [15] The verification included the reinforcing profile of the Sepals IGU's (see section 3.4), the dead load considering the two extreme positons of the Sepals (open and close) as well as the maintenance loads and the both kinds of climatic ones: external climatic loads (snow and wind) and the internal (height, atmospheric pressure, and temperature differences).

3.2 Retaining system

The retaining system for the IGU's is mainly a RAICO® THERM+ S-I 76 [16] fixing the IGU's and the lateral claddings that cover the steel profiles, as seen in Figure 8. Additionally, patch fittings are used in some joints of the fix base and the reinforcing profiles are bond to the IGU's by means of structural silicone, according to the detail seen in Figure 10.

Two verifications of the mechanical –RAICO®– retaining system were performed. First, the bolts pull-out (the least resistant part of the system) was verified under ULS loads (in open and closed positions) according to the principles of the German National Approval for the system [17]. Second, an approximate fatigue verification of the bolts pull-out was performed for the mechanical retaining system on the Sepals.

The fatigue verification of the bolts pull-out was a key issue for the glass retaining system, since the failure of the system would represent the fall out of the glass panels, which have a significant weight and dimensions. Furthermore, no information was found regarding the fatigue resistance of the system. Therefore, a conservative methodology, accorded with the rest of the design team, and engineering judgement based, was used for the verification. The methodology was as follows:

1. Obtaining of a "virtual resistant area" for the pull-out considering the characteristic values declared in [17] and the ultimate resistance of a stainless steel bolt of class 70 (700 MPa).
2. Determination of the stress ranges due to the dead load and the wind load. The stress range of the wind load was included to consider the wind induced fatigue in combination to the dead load as a conservative approach. The wind induced fatigue was based in the figure B.3 and expression B.9 of [18].
3. Use of the Palmgren-Miner rule as described in the annex A of [9] to sum the damage performed by the different fatigue loading events which must be less than the unit. The damage for each loading event is defined as the quotient of the number of cycles ($n_{E,i}$) over the number of cycles that would produce the failure ($N_{R,i}$) for the factorised stress range ($\Delta\sigma_i \cdot \gamma_{Ff} \cdot \gamma_{Mf}$) and the detail category ($\Delta\sigma_c$).

In the Table 1 the results of the fatigue verification are presented. The detail category of bolts and threaded bars was considered

Figure 7. IGU's in the NorthGlass® production plant in China (photos: NorthGlass®).

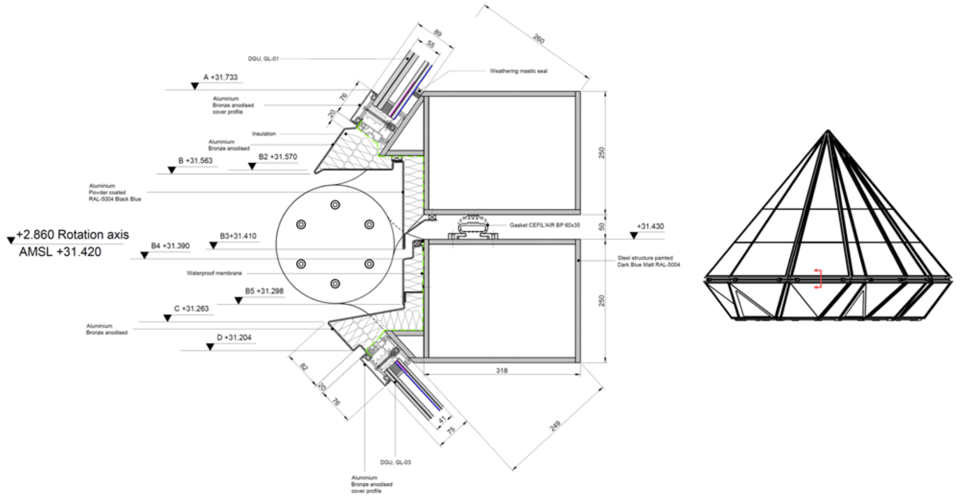

Figure 8. Retaining and weathertight systems in the hinge zone.

Table 1: Fatigue events and damage.

Case	Number of cycles (n_E)	Stress range ($\Delta\sigma_i \cdot \gamma_{Ff} \cdot \gamma_{Mf}$)	Maximum number of cycles (n_E)	Damage (n_{Ei} / N_{Ri})
Dead load	$5x10^4$	65.88 MPa	$8.74x10^5$	$5.72x10^{-2}$
Wind	$1x10^0$	166.44 MPa	$5.42x10^4$	$1.84x10^{-5}$
	$1x10^1$	138.65 MPa	$9.38x10^4$	$1.07x10^{-4}$
	$1x10^2$	113.18 MPa	$1.72x10^5$	$5.80x10^{-4}$
	$1x10^3$	90.04 MPa	$3.42x10^5$	$2.92x10^{-3}$
	$1x10^4$	69.24 MPa	$7.53x10^5$	$1.33x10^{-2}$
	$1x10^5$	50.76 MPa	$1.91x10^6$	$5.23x10^{-2}$
	$1x10^6$	34.62 MPa	$6.03x10^6$	$1.66x10^{-1}$
	$1x10^7$	20.81 MPa	$8.70x10^7$	$1.15x10^{-1}$
	$1x10^8$	9.32 MPa	$4.82x10^9$	$2.07x10^{-2}$
Total				0.43 < 1.00 -> Ok!

$\Delta\sigma_c = 50$. The partial factors have the standard value, namely: $\gamma_{Ff} = 1.0$ and $\gamma_{Mf} = 1.1$.

3.3 Glass carriers

Glass carriers disposal inside a RAICO® system is normally straight forward and its details are perfectly described in the manuals [16]. However, it is not straight forward when the glass units are irregularly shaped, its gravitational centre is not in the middle of its lower side (or even outside of it) or the supporting sides are not horizontal. This complicates when the glass units rotate in their plane during service, as happens in the side IGU's of the Sepals.

For having a precise understanding of the glass carriers loading an RFEM [5] model was made as shown in Figure 9. Even if all the considered glass carriers were necessary, for service or assembly, the system was overconstrianed for the thermal expansion of the IGU's. Therefore, some of the glass carriers were supplemented for the final adjustment with a deformable material (EPDM) instead of the conventionally used rigid plastic (POM-C). This way, significant stresses due to thermal expansion were avoided, lowering the risk of glass breakage.

3.4 Structural silicone joint

The structural silicone joint that bonds the reinforcing profile to the Sepal IGU's was verified under the principle that its failure would not cause the fall out of the glass, not even if it happened in the open position, since the mechanical fixations are able to hold the glass in this situation. A close communication and cooperation with the Sika® team was instrumental to achieve a satisfactory result as well as a deep understanding of their recommendations [19]. The results from the SJ-MEPLA® [14] models described in section 3.1 were used for the joints verification; being their maximum value 1.79 N/mm for the SLS (W+DL).

4. Structure Fabrication

The Woolbeding Glasshouse structure is composed by bespoke edgy tubes that meet in sharp angles and complex nodes. Furthermore, it is fatigue loaded (which demands full penetration butt welds with careful welding control) and has an aesthetic requirement (which implies polishing the welds were visible). This nature of the structure made the fabrication a challenge. In order to achieve the desired geometry and tolerances the structure was preassembled in Bellapart's workshop when welding avoiding undesired heat-related deformations (Figure 11). This preassembly was made using mild steel props and templates and with the bolts tight. Afterwards the bolts were loosened and no permanent deformation was observed.

5. Structure assembly and construction.

Construction began in mid-summer 2020 and finished in early summer 2021. The global pandemic was added to a by definition difficult process. The most delicate group of operations were related to the Sepals. They were assembled on site in horizontal position since the curvy and narrow roads of the English

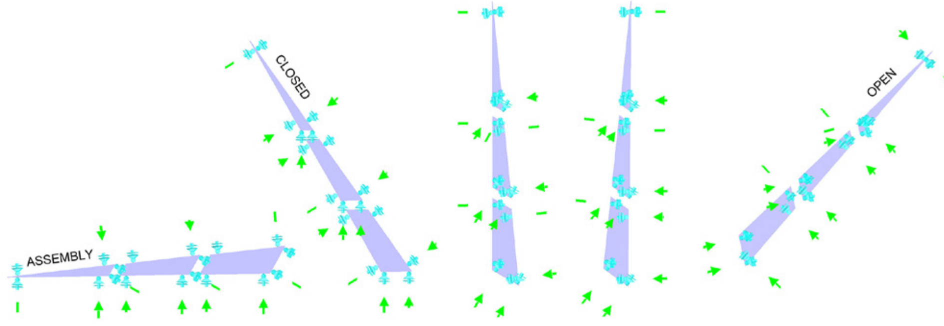

Figure 9. RFEM models for the lateral IGU's of the Sepal.

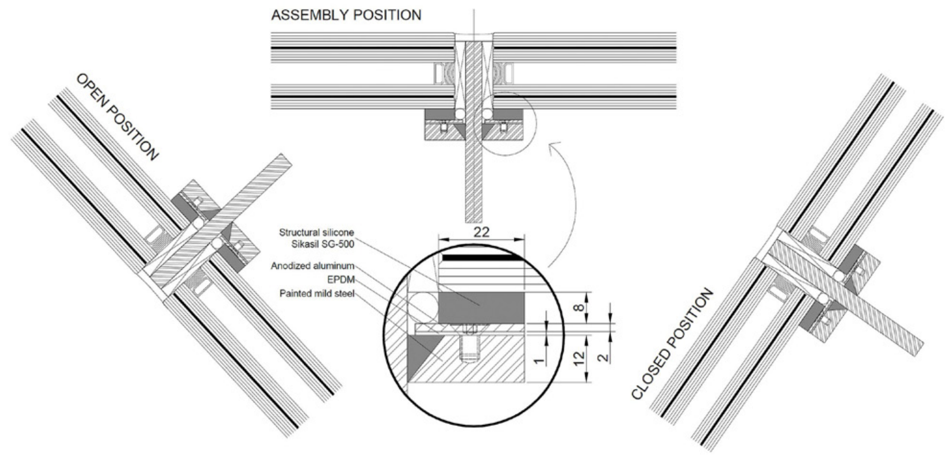

Figure 10. Steel reinforcing profile and structural silicone joint.

Figure 11. Fix base fabrication on Bellapart's workshop.

countryside forced the Sepals' profiles to be transported in three pieces. The horizontal assembly included most of the glazing and cladding, achieving each Sepal a weight around 8000kg. Then, they were lifted in their position on the top of the fix base (Figure 12) fixed with provisional clamps. The clamps were adjustable in the three dimensions and able to resist up to 250 kN (125 kN permanently). When all the Sepals were in their final place and the tolerances were adjusted, the hinges and the hydraulic cylinders were located and fixed in their final position and the provisional clamps retired.

Figure 12. Sepal's assembly on top of the fix base.

6. Conclusions

The Woolbeding Glasshouse is one of a kind building-machine hybrid which pushed the capacities of all the verification, design, fabrication and construction to the edge. Its complicated geometry combined with the moving Sepals and relatively remote site made the usual procedures in the industry difficult, forcing the design team to question the way things are normally done. A significant amount of effort, time and thought was invested in carefully analyze each and every one of the aspects of it, from the ones that did seem difficult (section 2, 4 and 5) to the ones that are normally more banal (section 3.3). The Woolbeding Glasshouse demonstrates that nothing is banal when you go beyond the common practice, even when using the same materials and systems.

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Compliance with ethical standards

Conflict of interest
On behalf of all authors, the corresponding author states that there is no conflict of interest.

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