EXOSKELETWINDOW

Thin-glass window embedded with soft pneumatic actuator

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Content

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2. Hypothesis-based research
3. Draft design
4. Mathematical model and assumption
5. Simulation and further design
6. Conclusion and discussion
Introduction
How window open for natural ventilation nowadays

Top hung window open to outside
Bottom hung window open to outside
Common window open to outside
Push-out window
Frameless sliding glass window

Top hung window open to inside
Bottom hung window open to inside
Common window open to inside
Push-out window
Double Hung Double-Glazed Sashless Window
- Unpredictable wind
- Monotonous window openings
- Difficult to control inlet air velocity and direction
Main questions

How can soft pneumatic actuator (SPA) bend thin-glass windows **structurally** for natural ventilation?
Sub-questions

- How to prove curved window can decrease predict dissatisfied percentage due to draft (PPDR)

- Considering natural ventilation function, which window configuration can be developed

- What is the relationship between SPA geometry, air pressure and bending radius.

- How to design window frame
Part 1.1

Methodology
Proof of Concept (POC)

Hypothesis

A: Soft pneumatic actuator can bend insulating thin glass window

B: Curved window can improve predict dissatisfied percentage due to draft
Proof of Concept (POC)

Hypothesis

A: Soft pneumatic actuator can bend insulating thin glass window
B: Curved window can improve predict dissatisfied percentage due to draft

Hypothesis based Research

A: Soft Pneumatic Actuator, thin glass and Window detail
B: Aerodynamic theory and Draught model
Proof of Concept (POC)

Hand calculation based approximation

A: Structure mechanism, SPA morphology generation

B: Inlet air flow rate
Proof of Concept (POC)

Hand calculation based approximation
A: Structure mechanism, SPA morphology generation
B: Inlet air flow rate

Simulation based approximation
A: Soft Fiber-Reinforced Bending Actuator, SPA
B: Mean air velocity and predict dissatisfied percentage due to draft (PPDR)
Proof of Concept (POC)

Experiment based evaluation

A: Model making by increase air pressure to test bending behavior
Hypothesis-based research
Future window

- High strength
- Flexibility
- Lightweight

Source: (Schott, 2016)
Previous research on thin glass topic

- Thin glass adaptive facade
  Source: (Rafael, 2016)

- Water and air tight bending facade
  Source: (Özhan, 2017)

- Folding-canopy roof
  Source: (Prof. Jürgen Neugebauer, 2014)

- Bamboo and thin glass roof
  Source: (Priyanka, 2016)

- Thin glass sandwich panel
  Source: (Iris, 2017)
Chemically strengthened borosilicate glass

**Chemical strengthened process**

**Stress cross-sectional of chemically strengthened glass**

**Stress on surface by bending curvature**

**MECHANICAL CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Property</th>
<th>Leoflex (0.85mm)</th>
<th>Thermally tempered (3.2mm)</th>
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<tbody>
<tr>
<td>Strength / Marginal stress</td>
<td>260</td>
<td>80</td>
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<tr>
<td>Young modulus</td>
<td>74</td>
<td>70</td>
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<tr>
<td>Poisson ratio</td>
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<tr>
<td>Density</td>
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</table>

Future window
New material possibilities

Wing-wall concept

Tilt and turn window concept
New material possibilities

Variable opening radius adaptable to external environment

\[ Q = C_d A v \]

Wing-wall concept

Tilt and turn window concept
CFD simulation comparison
Fanger and Pedersen (1977) experiments show that a fluctuating air flow is more uncomfortable than a constant flow with the same mean velocity.
CFD simulation comparison

Opening size-A/ Drag force 46/ Drag coefficient 1.64

Opening size-A/ Drag force 64/ Drag coefficient 2.10

Opening size-B/ Drag force 28/ Drag coefficient 1.18

Opening size-B/ Drag force 47/ Drag coefficient 1.78
Soft robotics

Source: (soft robotic toolkit, 2015)
Two soft actuators comparison

Soft Fiber-Reinforced Bending Actuators

- Elastomer
- Protection Layer
- Inner Chamber
- Strain Wrapping
- Strain Layer
- Fiber reinforcements
- FEM modeled soft actuator
- Inextensible layer
- Pressurized state

Source: (soft robotic toolkit, 2015)

Soft Pneumatic Actuator

- Extensible Layer
- Inextensible Layer
- Inside wall
- Top wall
- Chamber
- Paper Embedded Layer
- Unpressurized
- Pressurized

Source: (soft robotic toolkit, 2015)
Two soft actuators comparison

Soft Fiber-Reinforced Bending Actuators

Soft Pneumatic Actuator

Source: (soft robotic toolkit, 2015)
Relative Research- SPA- Actuator morphology influences air pressure

Conclusion

To achieve full bending motion,
Thinner wall, more chamber numbers and higher segments requires least air pressure

Source: (Mosadegh et al., 2014)
Relative Research- SPA- Variable Stiffness at different localities to conform to the shape
Structural mechanism

Inextensible layer

Stretching based bending

$M_{\text{stretch}} = ?$

Contacting based bending

$M_{\text{contact}} = ?$

$q$

$q$

$q$

$q$

$q$

$q$

$q$
Structural mechanism

Bending moment \((M)\) by pressure

Rubber tensile stress \((\sigma)\)

Thin glass tensile stress \((\sigma)\)

End edge deflection \((\delta)\)

\[
\frac{1}{R_1} = \frac{M_{\text{stretch}}}{EI} \quad \frac{1}{R_2} = \frac{M_{\text{contact}}}{EI}
\]
Product mechanism - stretching model
Product mechanism - strain energy method

- Gas compression
- Elastic rubber deformation
- Work added by an external load

\[ W = W_{\text{air}} + W_{\text{silicon}} + W_{\text{load}} \]

\[ h = 50\,\text{mm} \quad P = 0.55\,\text{MPa} \]

\[ \frac{\delta W_{\text{silicon}}}{\delta \lambda_1} + \frac{\delta W_{\text{air}}}{\delta \lambda_1} + \frac{\delta W_{\text{load}}}{\delta \lambda_1} = 0 \]

\[ d = 8\,\text{mm} \quad M_{\text{stretch}} = 189\,\text{Nmm} \]
Product mechanism - contacting model
Product mechanism - stretching and contacting model

\[ M_{\text{stretch}} = 189 \text{Nmm} \]

\[ M_{\text{contact}} = PAe = 2775 \text{Nmm} \]
Soft Robotics Technology Utilities

- **Gripper**
  - Octopus gripper - Festo
  - Soft Robotics gripper
  - Soft Robotics gripper

- **Rehabilitation**
  - Skewed rotary elastic chambers bending actuator
  - Soft robotic glove

- **Sun shading**
  - Adaptive Solar Façade installed at ETH House of Natural Resources
Soft Pneumatic Actuator-benefit

- Curvature adaptive
- Continuous form change
- Lightweight
- Easily controlled and measured
- Less mechanical equipment
Draft design
Hand sketches

- Bi-direction opening window
- Variable stiffness with jamming chamber
- Top hung window
- Four opening directions prototype

Future window
Design A

Design B
ΔP_1 = 0
ΔP_2 < 0
Phase 1: Closed

ΔP_1 = 0
ΔP_2 = 0
Phase 2: Prepare opening

ΔP_1 > 0
ΔP_2 = 0
Phase 3: Start opening

ΔP_1 = 0
ΔP_2 < 0
Phase 4: Keep opened
Design D
Parametric geometry generation
Mathematical model and assumption
Opening size calculation

Opening size \( = L (\sin \theta + \sin 2\theta + \sin 3\theta + \ldots + \sin n\theta) \)

\[ \theta = \frac{L_2}{R_2} \]

\[ \sigma = \frac{ET}{2R_2} \quad \theta = \frac{LM_2}{EI} = \frac{L}{R} \]
Product mechanism - rigid spacer

Flexural rigidity = $E_1 I_1 + E_2 I_2$

$\sigma_{1\text{max}} = \pm \frac{M(h/2)E_1}{E_1 I_1 + E_2 I_2}$

$\sigma_{2\text{max}} = \pm \frac{M(h_c/2)E_2}{E_1 I_1 + E_2 I_2}$

$R = \frac{E_1 I_1 + E_2 I_2}{M}$

$t = 0.55\text{mm}$

$h_c = 12\text{mm}$

$M = 2775\text{Nmm}$

$R = 346\text{m}$

$I_1 = \frac{b}{12}(h^3 - h_c^3)$

$I_2 = \frac{b}{12} h_c^3$
Correction: Soft actuator morphology - enlarge bending moment

\[ n = 25 \]
\[ M = 210000 \text{Nmm} \]

\[ h_e = 4 \text{mm} \]
Energy Efficient

80% of the energy lost through a window occurs at the edge of the glass because of the highly conductive nature of aluminium spacer. Super Spacer® is 950 times less conductive, blocking heat loss and reducing energy costs. Super Spacer reduces window U-values by up to 0.2W/m²K allowing windows to achieve the highest Window Energy Ratings.

Download the leaflet

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Product mechanism - effective flexural stiffness of insulating window - correction

0.55mm thickness thin glass and 12mm super spacer

\[ I_1 = \frac{b_1}{12} (h_3^3 - h_c^3) \]

\[ I_2 = \frac{b_2}{12} h_c^3 \]

Flexural rigidity = \( E_1 I_1 + E_2 I_2 = 1.9 \times 10^9 \text{ N mm}^2 \)

\[ I_1 = \frac{b_1}{12} t_3^3 \]

\[ I_2 = \frac{b_2}{12} h_c^3 \]

Flexural rigidity = \( 2E_1 I_1 + E_2 I_2 = 1.3 \times 10^6 \text{ N mm}^2 \)
Calculation integration

Future window

Ventilation

glass moments of inertia (mm^4)

super spacer moments of inertia (mm^4)

composite plate flexural rigidity (Nmm^2)

bending moment (Nmm)

stress on thin glass (MPa)
Calculation integration

- Thin glass moments of inertia (mm4)
  - Window width
  - Linear coefficient
  - Linear fiber

- Super spacer moments of inertia (mm4)
  - Spacing length
  - Linear coefficient
  - Linear fiber

- Composite plate flexural rigidity (Nmm2)
  - Linear coefficient
  - Linear fiber

- Bending moment (Nmm)
- Stress on thin glass (MPa)

- Future window
Draft experiment
Material property

- Tensile strength: 6.5MPa
- Elongation at break: 700%
- Break at air pressure: 1 bar

Disadvantage

- Low tensile strength: 6.5MPa
Material property

Tensile stress at yield: 8.6 MPa
Elongation at break: 580%
Maximum air pressure: 4 bars

Disadvantage

High tensile modulus: 26 MPa
Leakage between layers
## Production and cost

<table>
<thead>
<tr>
<th>Description</th>
<th>x</th>
<th>y</th>
<th>z extents (mm)</th>
<th>Quantity</th>
<th>Unit</th>
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<tbody>
<tr>
<td>FDM: Material= Nylon 12</td>
<td>77.209<em>46.511</em>30</td>
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<td>FDM: Material= ABS</td>
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<td>$324</td>
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</tbody>
</table>
Material property

Tensile stress at yield: 11 MPa
Elongation at break: 600%
Maximum air pressure: 7 bars
Part 4.2

Further design
Inspiration- Bellows grippers Festo
Inspiration - Bellows grippers Festo
Bellows connection remove
Bellows geometry generation

Design A

Design B
Bellows geometry generation

- Decreasing segments height
- Keep contacting area same
- Decreasing segments thickness
- Fillet bellow corners
Mould making and Production
Mould making and Production
Design A

Top view

Clamping edge

Rendering
Design B

Top view

Rendering
Design C - bottom edge clamping method

Clamping method A

Compression state

Shear state

Clamping method B

Opening on side edge
Design C

Inside view

Outside view
Part 4.3

Installing process
Future window

Side edge frame installing

Top edge frame installing
Thin glass panel edge painting
Bottom edge clamping
Bottom edge clamping
SPA support installing  
SPA installing  
Finishing
Part 5

Simulation
Flexural rigidity = $2E_{\text{thin glass}} I_{\text{thin glass}} + E_{\text{super spacer}} I_{\text{super spacer}}$

= $E_{\text{equivalent}} I_{\text{equivalent}}$

Thickness = 1.1mm

$E_{\text{equivalent}} = 84556 \text{MPa}$
Pressure correction
Validation

- Thin glass moments of inertia (mm^4)
- Super spacer moments of inertia (mm^4)
- Bending moment (Nmm)
- Stress on thin glass (MPa)
- Composite plate flexural rigidity (Nmm^2)

Ventilation

- Opening area
- Number of persons
- Velocity
- Velocity
- Velocity
- Air pressure
Material inflating comparing

Segments inflating deformation

Segments inflating stress simulation

Tensile strength: Natural rubber 28MPa
Elastosil silicone 6.5MPa
Indoor comfort simulation
Inlet air temperature
- 5°C lower than radiant temperature
- 3°C increasing need 0.8m/s increasing
- 5°C higher than radiant temperature
- 3°C increasing need 1.6m/s increasing

Maximum allowable elevated airspeed is 1.5 m/s
How to quantify indoor comfort by ventilation

- Air temperature ($t_a$)
- Mean air velocity ($\bar{v}$)
- Turbulence intensity ($Tu$)

Percentage Dissatisfied due to draft

$$PD = 3.143(34 - t_a)(\bar{v} - 0.05)^{0.6223} + 0.3696\bar{v}Tu(34 - t_a)(\bar{v} - 0.05)^{0.6223}$$

for $\bar{v} < 0.05$ m/s insert $\bar{v} = 0.05$ m/s

for PD > 100% use PD = 100%

Fig. 19. A three-dimensional representation of the draught-risk model. The surfaces shown correspond to 10%, 15% and 20% dissatisfied respectively. The axes are turbulence intensity, mean air velocity and air temperature.

Source: (Fanger, 1988)
Standard room configurations

Air exhausting

Air circulation

Single side ventilation
Standard room for simulation

- Wind velocity
- Air temperature
- Inlet airflow rate $Q \ (m^3/s)$
- Outlet
- Air temperature ($t_a$)
- Mean air velocity ($\bar{v}$)
- Turbulence intensity ($Tu$)
- 1.1m
Phoenics CFD simulation

Room A

Room B

PPDR in room A

PPDR in room B
Phoenics CFD simulation

PPDR in room A

Air speed in room A

PPDR in room B

Air speed in room B
Phoenics CFD simulation

PPDR in room A

Air speed in room A

PPDR in room B

Air speed in room B
Phoenics CFD simulation

Turbulence intensity in room A

Turbulence intensity in room B

PPDR in room A

PPDR in room B
Part 5.2

Benchmark Exoskeletonwindow
Window opening configurations
Product features

- Smooth air flow rate changing ratio
- Adaptive hinge system
- Low maintenance compared to kinetic façade
- Easy to control and measured
- Meet different architecture function and aesthetic
Part 5.3

Case study
Google map view

TPM Building facade

Window hinge system
Conclusion and discussion
### Advantage

- Automatically indoor environment improving by responding to the external environment
- No motors and mechanical equipment
- Lightweight
- Potential on geometry generation

### Disadvantage and limitation

- Low insulation value
- Too large window frame
- The low durability of rubber material
- Risk of delamination between silicone and thin glass

**Conclusion:** Not ready for the market, but worth further researching
Limitation of research

- Wind load and wind direction effect on structure are not considered
- Rubber material biaxial and uniaxial testing for Abaqus simulation
- CFD analysis in different configurations
  - Different window opening size
  - Different window locations
  - Different outlet locations
Future research

- Geometry generation
- Effects of wind load and direction
- Window location and opening size optimization to improve indoor comfort
- SPA material exploration
- Sun shading integration
Physical model
Exploration
Wing wall configurations