A Photogrammetry-Based Method for Membrane Surface Strain and Stress Measurement

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Content

1 Research background

2 Experiment content

3 Results and discussion

4 Conclusions

Membrane health monitor

- Membrane working condition
  - Surface stress
  - Surface strain
- …

Drone platform

Possible applications

- **Photogrammetry-based** measurement
- Applicable for **large scale** surface (1-10m)
- Relatively accurate result

New strain measurement Method

New requirement

Digital Image Correlation (DIC)

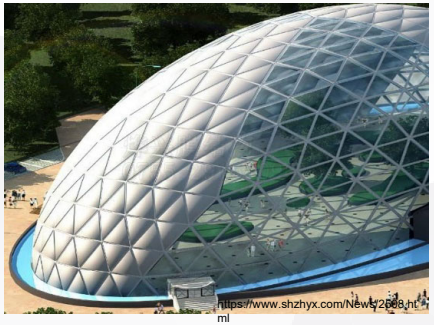
Advantages:

- Non-contact measurement
- High resolution and accuracy

Disadvantages:

- Strict optical environment
- Strict measurement condition
- Limited to small size object (100 mm)

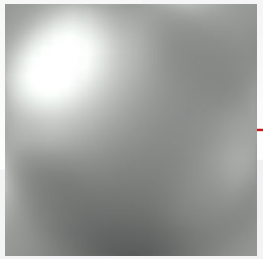
Challenging



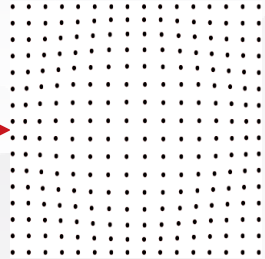
Oriental Eden Project

Water Cube

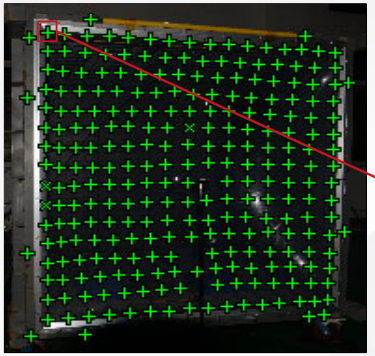
Large scale membrane structures

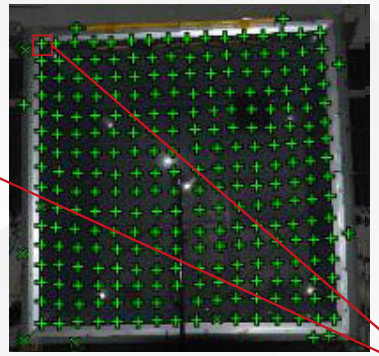


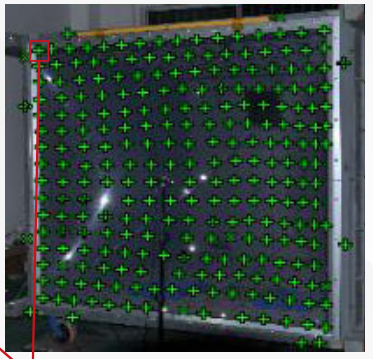
Membrane surface



Surface point-cloud array

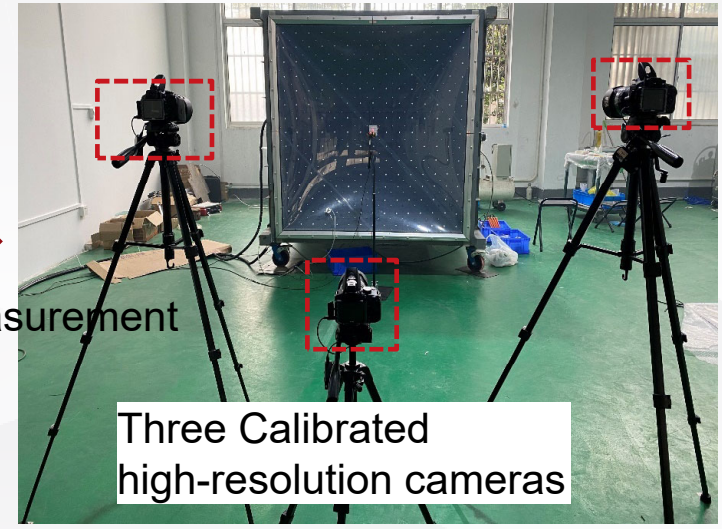


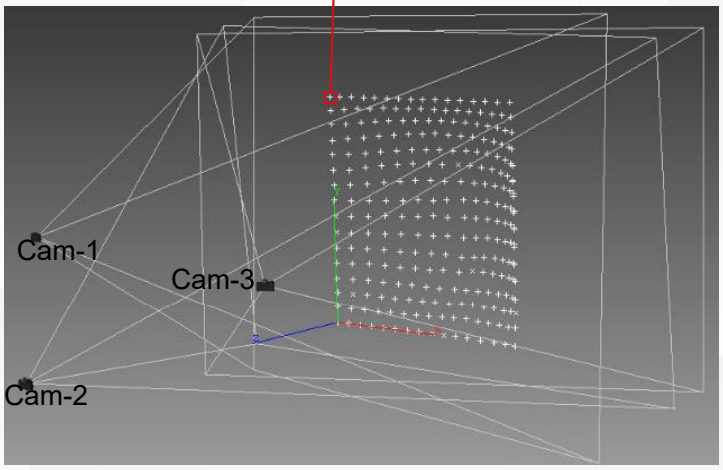




Point-to-point reference

Photogrammetry-based measurement

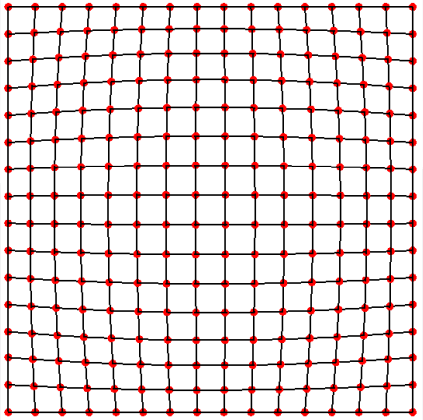




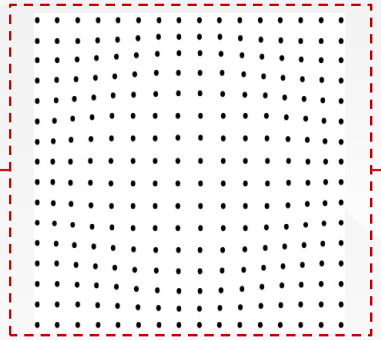
Flash-reflective target array

Optical measurement

Target array coordinate derivation

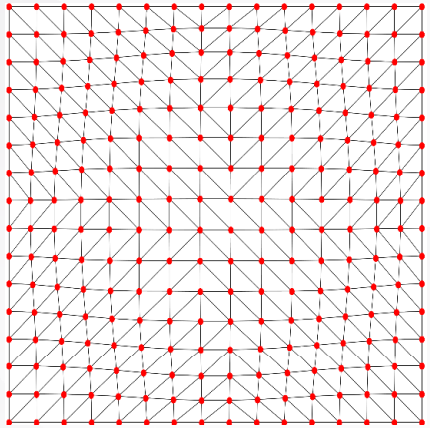


Node topology



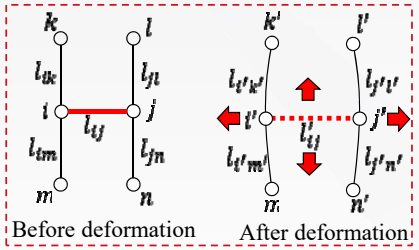
Surface point-cloud array

Node topology

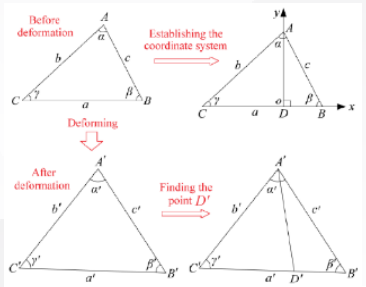


Virtual cable network

Triangular face element

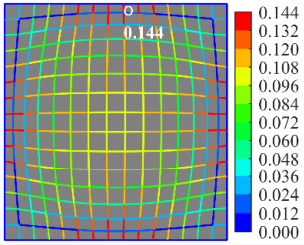


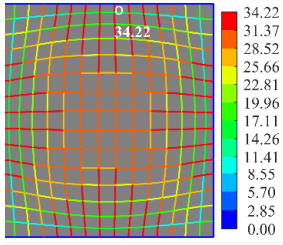
Constant strain element (CSE) assumption



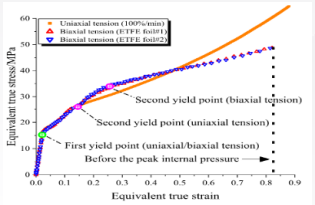
Cable elongation

Geometry computation





Cable strain

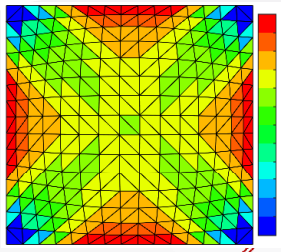


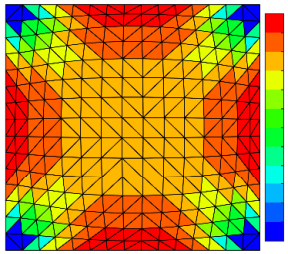
Material property

Element strain

Cable stress

Element stress

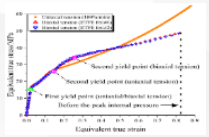




Cable(LINE) strain & stress

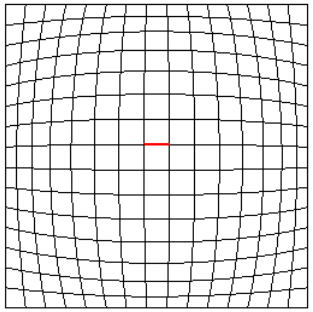
Triangular FACE strain & stress

Computation flow of Cable-network strain and stress distribution

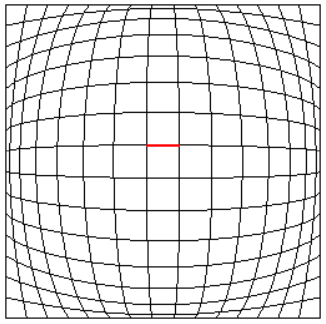


Stress-strain curve $\sigma(\varepsilon)$

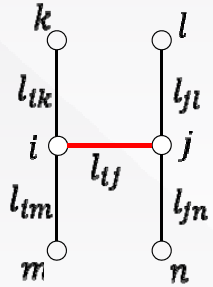
Virtual cable network → Cable elongation → Cable strain → Material property → Cable Stress



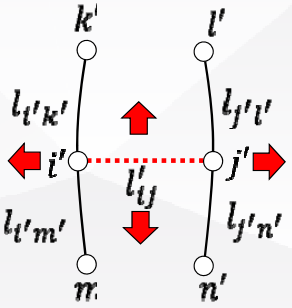
Unformed network



Deformed network



Undeformed length



Deformed length

- Cable elongation

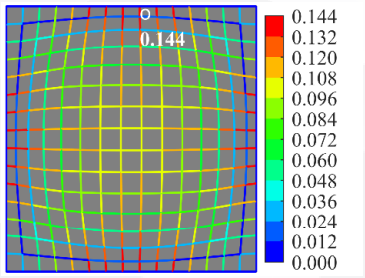
$$\Delta l = l'_{ij} - l_{ij}$$

- Engineering strain

$$\bar{\varepsilon} = \frac{\Delta l}{l_{ij}}$$

- True strain

$$\varepsilon_{11} = ln(1 + \bar{\varepsilon})$$



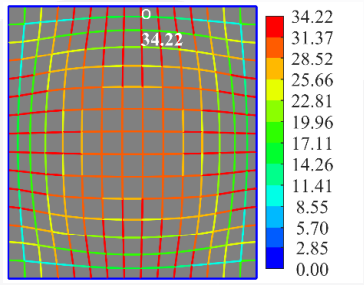
- Uniaxial stress-strain curve

$$\varepsilon_{ij} = \frac{1}{1-\nu^2}\varepsilon_{11} + \frac{\nu}{1-\nu^2}\cdot\varepsilon_{22}$$

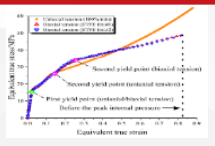
$$\sigma_{ij} = \sigma_{uniaxial}(\varepsilon_{ij})$$

- Biaxial stress-strain curve

$$\sigma_{ij} = \sigma_{biaxial}(\varepsilon_{ij})$$

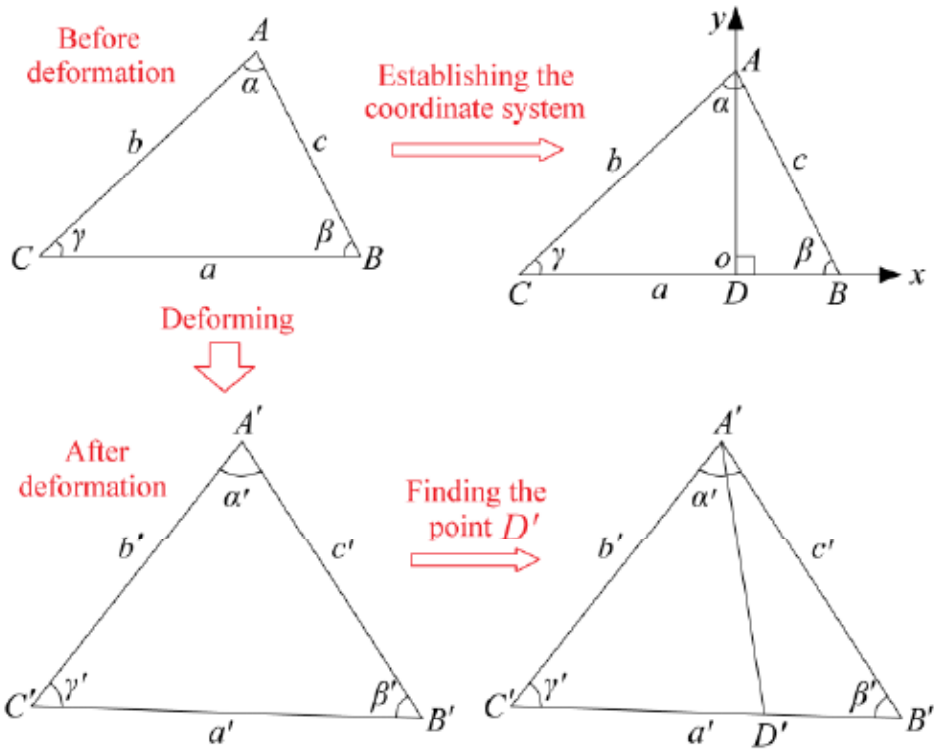


Computation flow of Triangular element strain and stress distribution



Stress-strain curve $\sigma(\varepsilon)$

Triangular face element → Geometry computation → Element strain → Material property → Element Stress



Element side length → l_{AB}, l_{AC}, l_{BC} $l_{A'B'}, l_{A'C'}, l_{B'C'}$

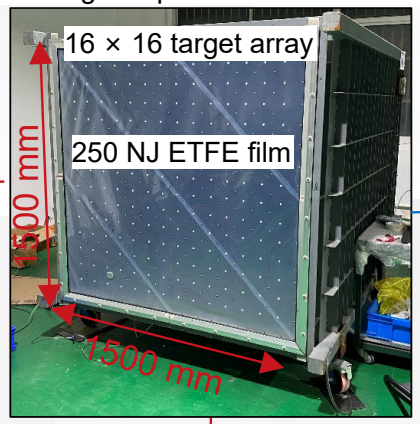
Uniform deformation → $\frac{l_{CD}}{l_{CB}} = \frac{l_{C'D'}}{l_{C'B'}}$

Internal side length → l_{AD}, l_{CD}, l_{BD} $l_{A'D'}, l_{C'D'}, l_{B'D'}$

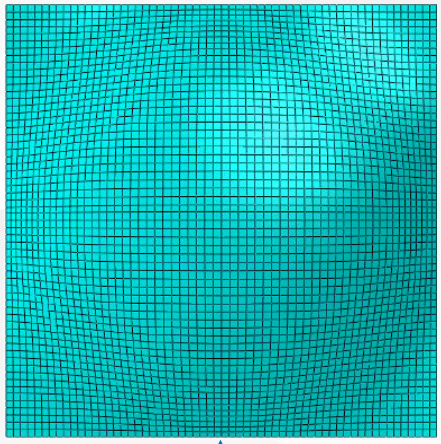
(R)Cauchy-green strain → $\mathbf{F} = \frac{\partial \mathbf{x}}{\partial \mathbf{X}} = \frac{d\boldsymbol{s}}{d\boldsymbol{S}}$ $\mathbf{C} = \mathbf{F}^{\mathrm{T}}\mathbf{F}$

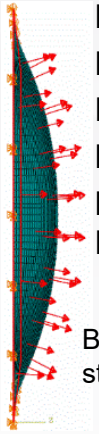
Green-Lagrange strain → $\mathbf{E} = \frac{1}{2}(\mathbf{C} - \mathbf{I}) = \frac{1}{2}(\mathbf{F}^{\mathrm{T}}\mathbf{F} - \mathbf{I})$

Loading compartment & ETFE film



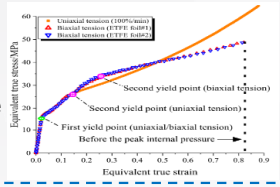
FEA



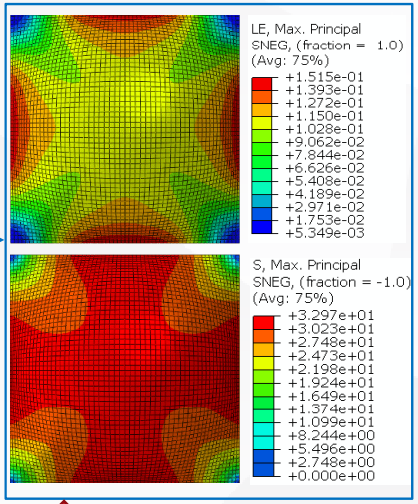


Element type: S4R
Boundary condition: pin
Loading type : Uniform suction
Mesh type: quadrilateral
Material property:
Nonlinear elastic-plasticity model

Biaxial tensile stress-strain curve



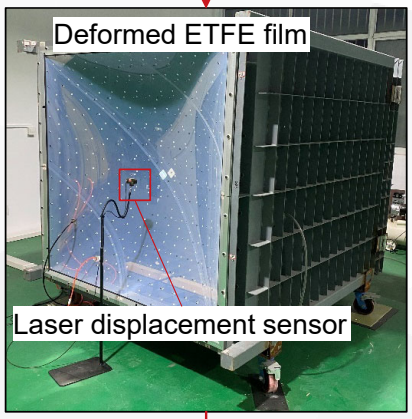
$P_{sim} = P_{exp}$
$u_{sim} = u_{exp}$

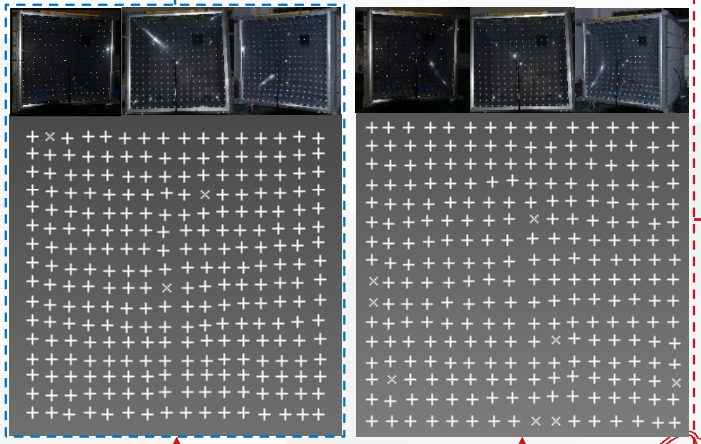


Uniform suction load
Rate = 1.2 kPa/min
Range = 0-15 kPa

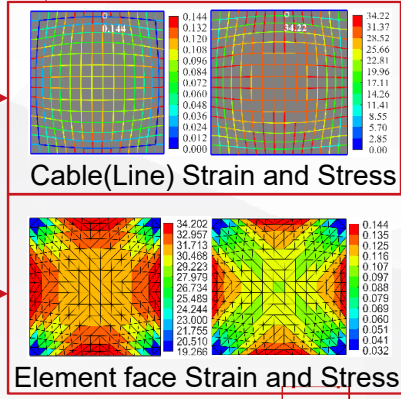
Initial surface modelling

Optical measurement system



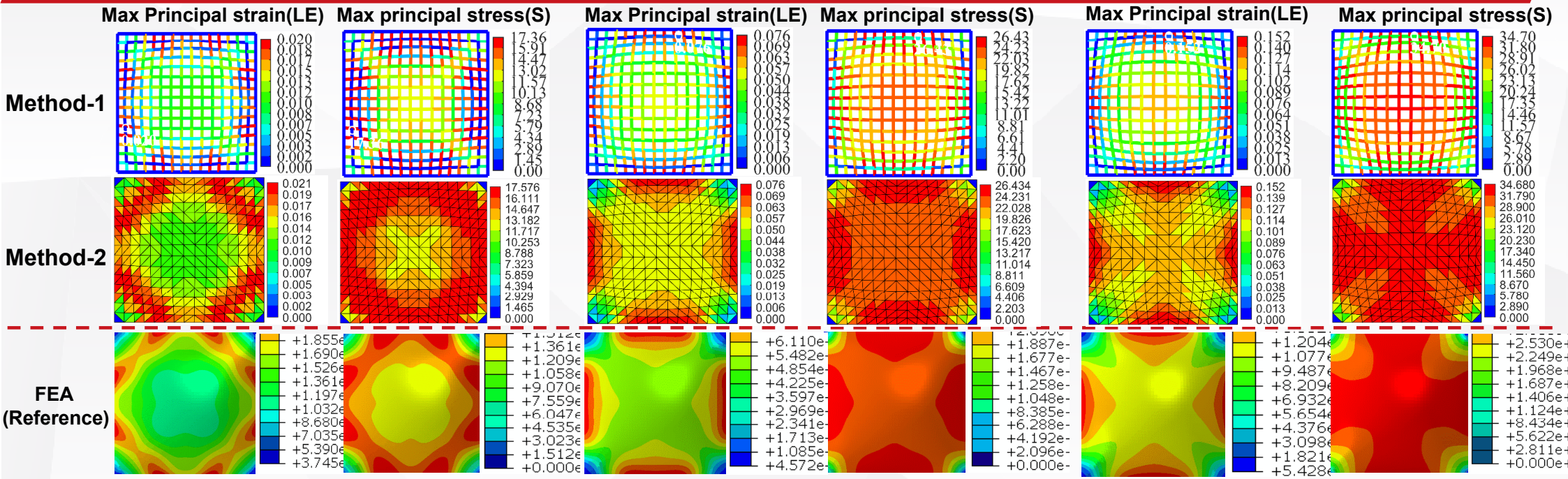


Comparison



Initial surface of ETFE film

Deformed surface of ETFE film



Suction load	4 kPa				8 kPa				12 kPa			
	Max LE	Error	Max. S	Error	Max LE	Error	Max. S	Error	Max LE	Error	Max. S	Error
Method-1	0.020	-13.0%	17.36	-4.3%	0.076	-3.8%	26.43	+5.0%	0.152	-4.4%	34.70	+2.8%
Method-2	0.021	-8.7%	17.57	-3.1%	0.076	-3.8%	26.43	+5.0%	0.152	-4.4%	34.68	+2.8%
FEA(reference)	0.023		18.14		0.079		25.15		0.159		33.73	

Conclusion

- Two methods are **valid and accurate** for measuring surface strain in large-size and deformation.
- The computation complexity of **triangular element method** is higher while the result is more precise.

Limitation

- The Constant Strain Element (**CSE**) assumption is **not solid** in **large size surface** and may results in considerable error
- **Stress estimation** depends on material property, which is relied on material test methods.

Thank you for listening

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