# Impact Analysis of Space Structure due to Collision with Hypervelocity Space Debris by using ASI-FEM

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**ISS**

**Prediction of damage against space debris collisions**

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**Numerical approach**

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**Strong non-linearity and discontinuity**

# Adaptively Shifted Integration (ASI) technique

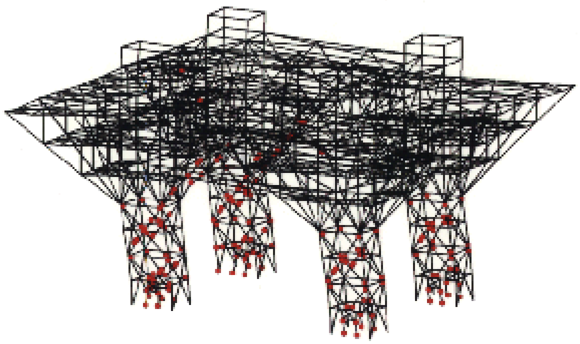
- **Very clear physical meanings**

  **comparing strain energy approximations**

  **FEM model ⟷ RBSM(Rigid-Bodies Spring Model)**

- **Simplicity**

  **easy to implement into FEM codes**



- **Low computational cost**

  **accurate solutions by minimum number of elements**

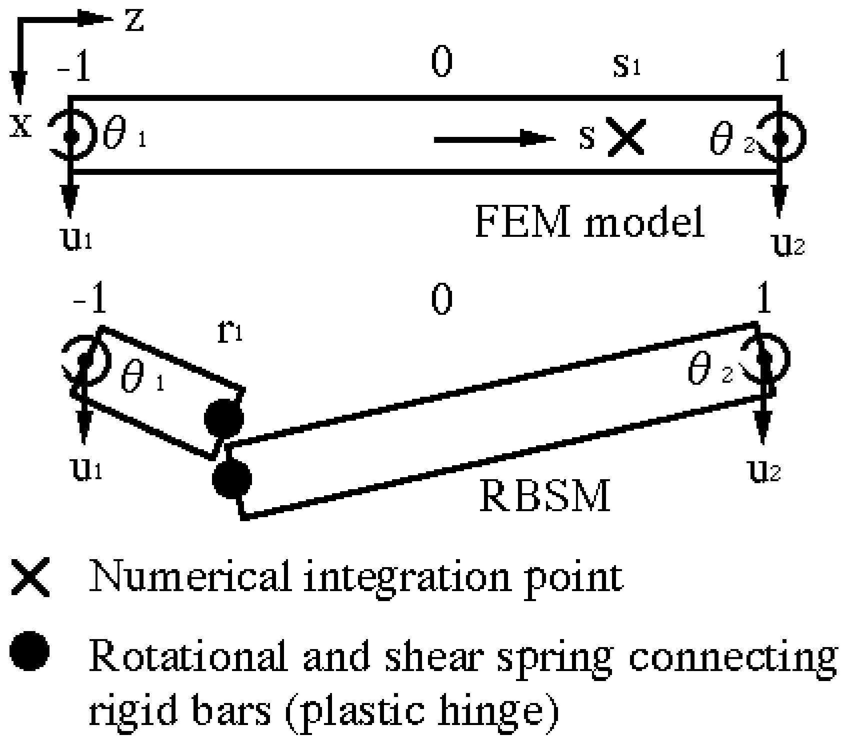



Fig.1 Linear Timoshenko beam element and its physical equivalent

**Relation between the location of a numerical integration point and a plastic hinge**

$$s_1 = -r_1 \quad or \quad r_1 = -s_1$$

**where**

**$s_1$:position of a numerical integration point**

**$r_1$:position of a plastic hinge or a fractured section**

# Incremental stiffness matrix and initial stress matrix

**・Elastically deformed element**

$$[{}^{n}_{n}\bar{K}_L] = \int_{{}^{n}l} [{}^{u}T]^T \cdot [{}^{0}T]^T [{}^{n}_{n}\bar{B}_L(0)]^t [D^e(0)] [{}^{n}_{n}\bar{B}_L(0)] [{}^{0}T] \cdot [{}^{u}T] dl$$

$$[{}^{n}_{n}\bar{K}_{NL}] = \int_{{}^{n}l} [{}^{u}T]^T \cdot [{}^{0}T]^T [{}^{n}_{n}\bar{G}(0)]^t [{}^{n}_{n}\bar{S}(0)] [{}^{n}_{n}\bar{G}(0)] [{}^{0}T] \cdot [{}^{u}T] dl$$

**・Element with a plastic hinge at its left end**

$$[{}^{n}_{n}\bar{K}_L] = \int_{{}^{n}l} [{}^{u}T]^T \cdot [{}^{0}T]^T [{}^{n}_{n}\bar{B}_L(1)]^t [D^p(-1)] [{}^{n}_{n}\bar{B}_L(1)] [{}^{0}T] \cdot [{}^{u}T] dl$$

$$[{}^{n}_{n}\bar{K}_{NL}] = \int_{{}^{n}l} [{}^{u}T]^T \cdot [{}^{0}T]^T [{}^{n}_{n}\bar{G}(1)]^t [{}^{n}_{n}\bar{S}(-1)] [{}^{n}_{n}\bar{G}(1)] [{}^{0}T] \cdot [{}^{u}T] dl$$

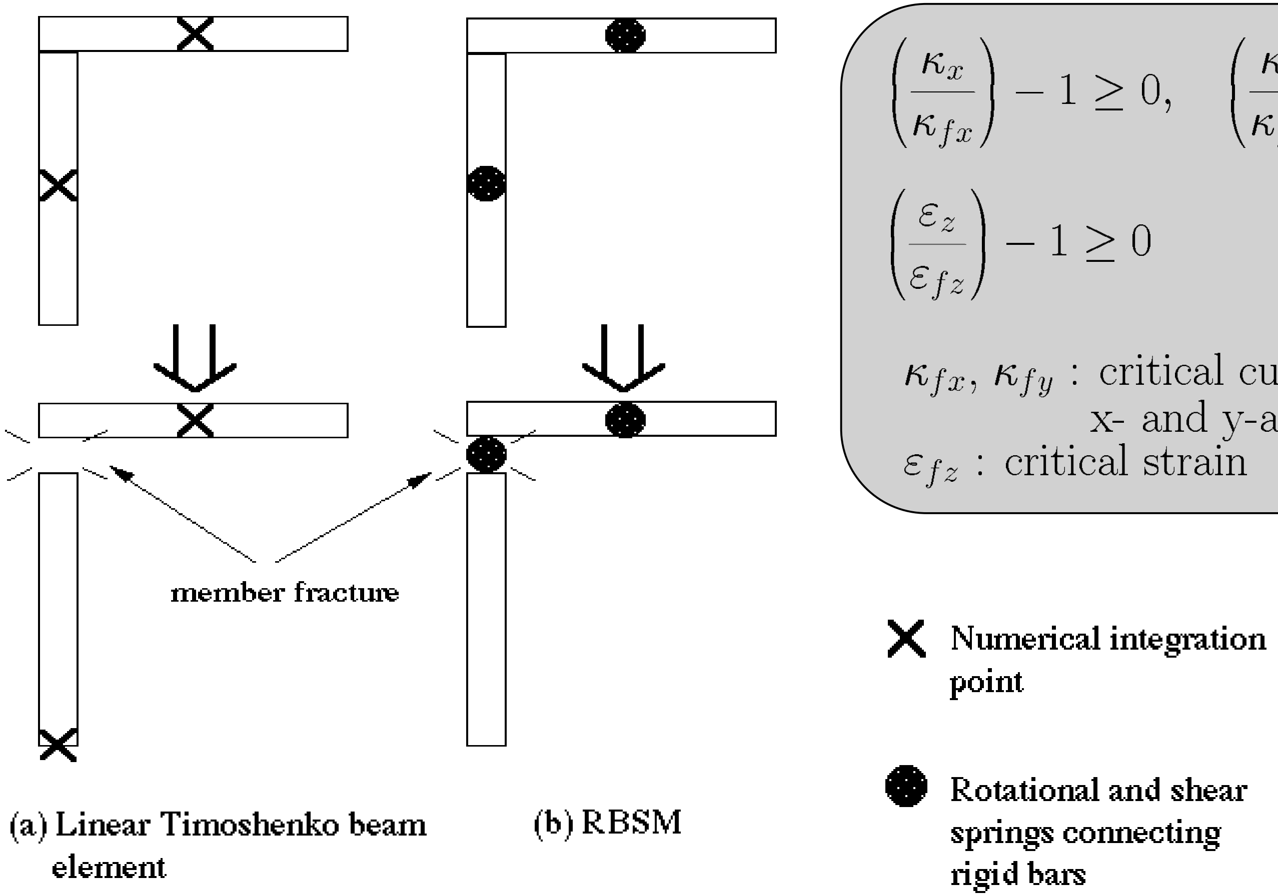
**・Internal force vector (elastic element)**

$$\{{}^{n}_{n}F\} = \int_{{}^{n}l} [{}^{0}T]^T \cdot [{}^{u}T]^T \cdot [{}^{n}_{n}\bar{B}_L(0)]^T \cdot \{{}^{n}_{n}\bar{R}(0)\} dl$$

**・Released force vector (fully-plastic or fractured element)**

$$\{{}^{n}_{n}F\} = \int_{{}^{n}l} [{}^{0}T]^T \cdot [{}^{u}T]^T \cdot [{}^{n}_{n}\bar{B}_L(1)]^T \cdot \{{}^{n}_{n}\bar{R}(-1)\} dl$$

# Criteria for member fracture




$$\left(\frac{\kappa_x}{\kappa_{fx}}\right) - 1 \geq 0, \quad \left(\frac{\kappa_y}{\kappa_{fy}}\right) - 1 \geq 0,$$

$$\left(\frac{\varepsilon_z}{\varepsilon_{fz}}\right) - 1 \geq 0$$

$\kappa_{fx}, \kappa_{fy}$ : critical curvature around x- and y-axes

$\varepsilon_{fz}$ : critical strain

Fig. Member fracture in the ASI technique

# Conditions for the elements in contact algorithm

## Four nodes on a same plane from the initial stage

$$
\begin{aligned}
f(x,y,z) \equiv\ & \{(y_{i1}-y_{f2})(z_{i2}-z_{f2})-(y_{i2}-y_{f2})(z_{i1}-z_{f2})\}(x_{f1}-x_{f2}) \\
&+\{(x_{i2}-x_{f2})(z_{i1}-z_{f2})-(x_{i1}-x_{f2})(z_{i2}-z_{f2})\}(y_{f1}-y_{f2}) \\
&+\{(x_{i1}-x_{f2})(y_{i2}-y_{f2})-(x_{i2}-x_{f2})(y_{i1}-y_{f2})\}(z_{f1}-z_{f2}) = 0
\end{aligned}
$$

**and existing in a specific distance**

$$|\overline{A_1B_{i1}}| + |\overline{A_1B_{i2}}| \le L_i, \quad |\overline{A_2B_{i1}}| + |\overline{A_2B_{i2}}| \le L_i$$

## Not on a same plane, but <u>nearly</u> forming a plane

$$f(x,y,z) \le 5.0 \times 10^6$$

**and existing in a specific distance**

$$|\overline{A_1B_{i1}}| + |\overline{A_1B_{i2}}| + |\overline{A_2B_{i1}}| + |\overline{A_2B_{i2}}| \le 1.8(L_f + L_i)$$

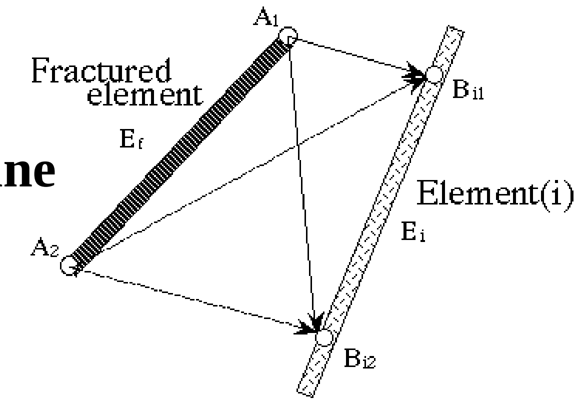



Fig.2a Contact conditions for a fractured element

## Binding conditions for the gap elements

- **Four gap elements between the two elements in contact**
- **Same material properties with other elements**
- **Stiffness decreases after certain time steps**

$(1.0 \times 10^{-3}\ \mathrm{sec})$

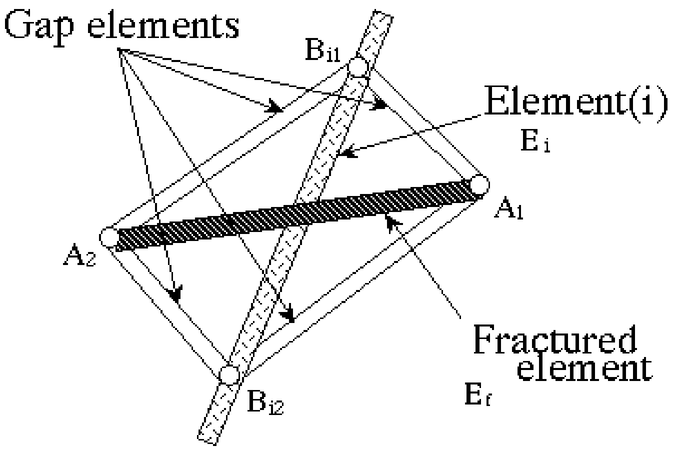
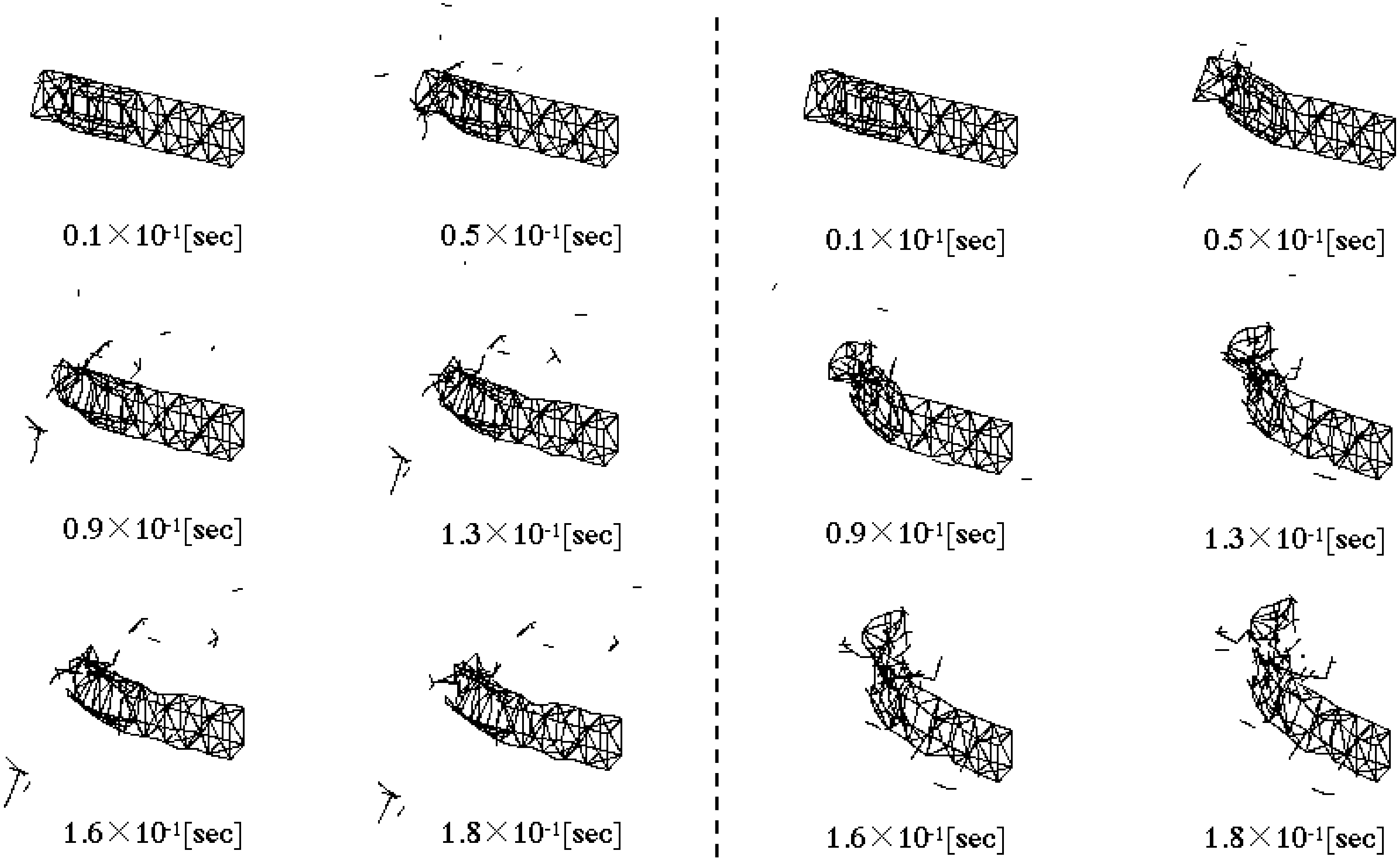



Fig.2b Gap elements in contact algorithm

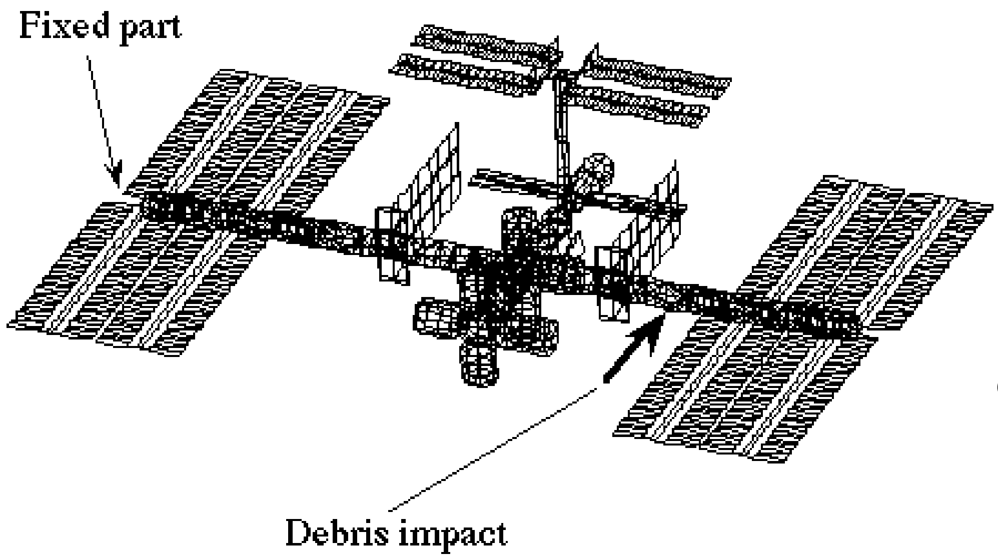
# Numerical examples




(a) without contact algorithm (b) with contact algorithm

Fig. Debris impact analysis of a space module unit (5 km/sec)

# Debris impact analysis of ISS



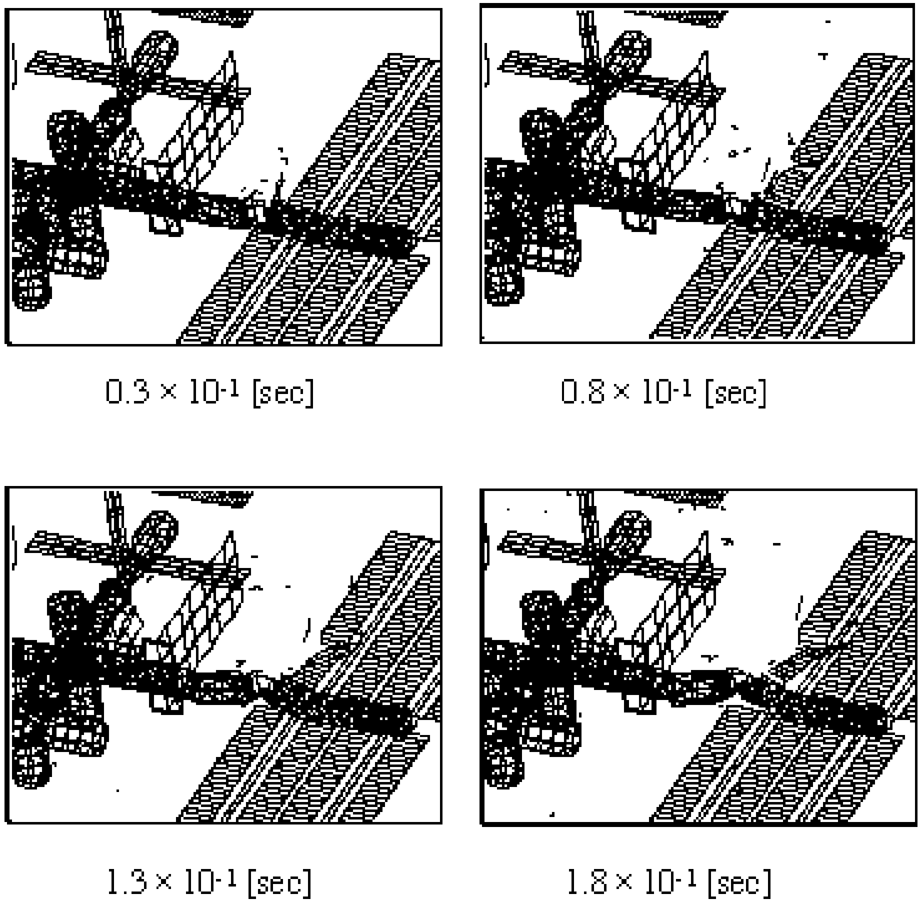

**9764 elements**
**7207 nodes**

**Debris**
**mass: 10 kg**
**velocity: 5 km/sec**

**Critical values for member fracture**

$$\kappa_{fx} = \kappa_{fy} = 1.0 \times 10^{-3}$$
$$\varepsilon_{fz} = 3.0 \times 10^{-1}$$

Fig.3 Analyzed model of ISS




Implicit scheme
(Newmark's $\beta$ method)
Incremental time:
$\Delta t = 0.4 \times 10^{-4}$ sec

Fig.4 Hypervelocity debris impact analysis of ISS

# Concluding remarks

**ASI technique**

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**Debris impact analysis**

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**Practical expression of the damage・process**

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**Strong nonlinear (discontinuous) problems easily analyzed by FEM**

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**・・ may be applied to Structural design process of space structures**