Detection of damaged components in 3-D frame structures via experimental design

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Outline of Presentation

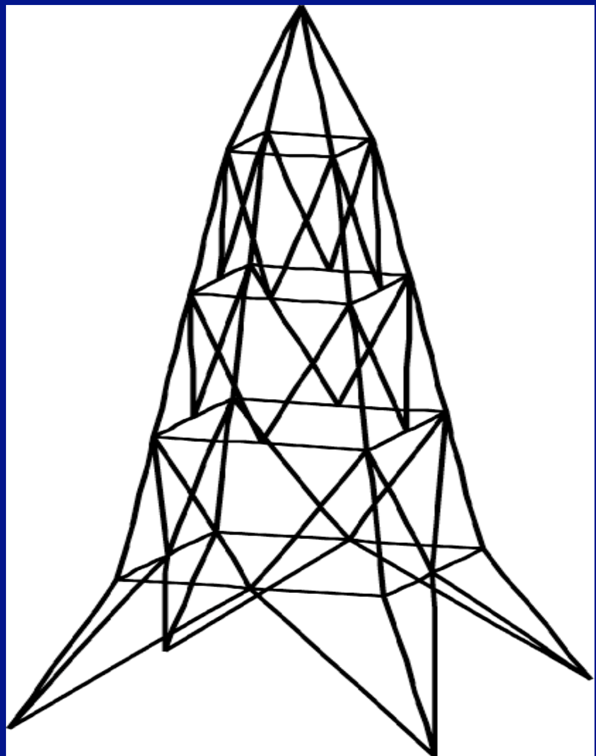
- Background
- Theory
  - Experimental Design
  - Evaluation Function
- Flow of Analysis
- Example Computations
- Concluding Remarks

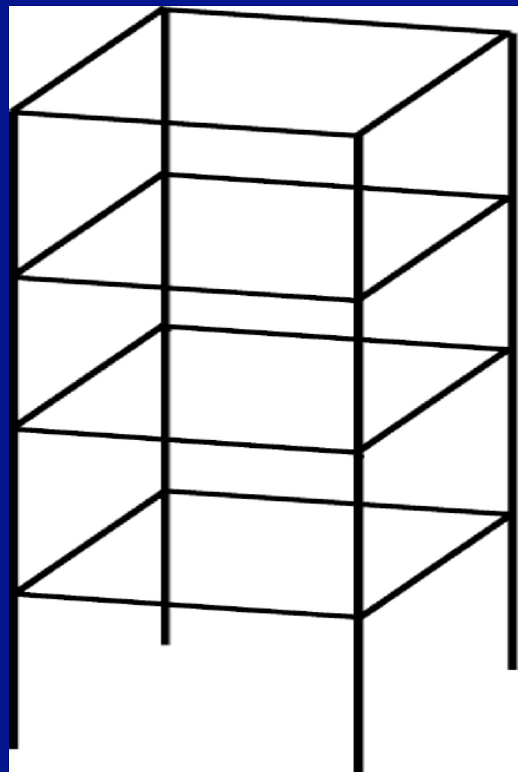
Background

There ia a wide variety of structures in the world.

Background

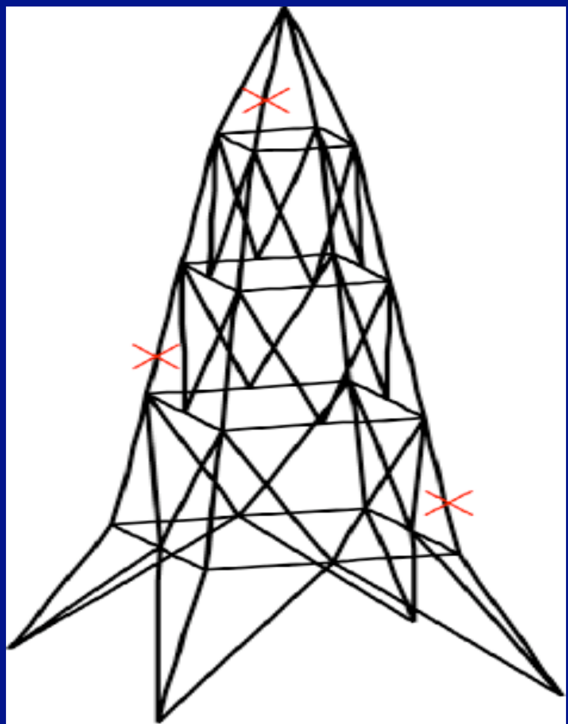
Many structures can be modeled as a frame structure.

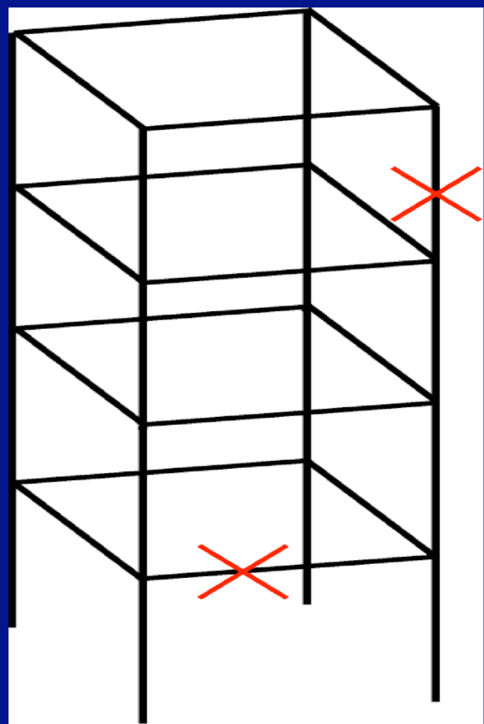




Background

For health monitoring of the structure, it is important to develop a computer system to identify the damaged components and their damage levels, using the measured data.





Background

A computational procedure is available for dynamic displacements of a frame structure.

Displacement responses are different if damaged components and their damage levels are different.

Sensitivity-based Optimization

Experimental Design

Combinational Optimization Using Orthogonal Table

Assumptions

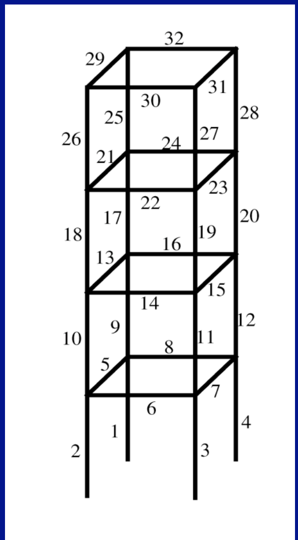
- Each component of the frame structure is straight and has extensional, bending and torsional rigidities.
- Damage is interpreted as reduction of Young’s modulus.
- Damage is implemented as three levels of Young’s modulus.

Experimental Design

- Analysis of each factor's influence on evaluation function using the orthogonal table
- Analysis of many factors by a smaller number of computations

Factor → Component
Level → Damage level

Example: Analysis of structure composed of 32 components by three levels of damage



Computations for all combinations:
$3^{32} \fallingdotseq 1.85 \times 10^{15}$
Computations using orthogonal table:
216 to 2268

Evaluation

Evaluation function U_n is defined by

$$U_n = \sum_{i=1}^{I}\sum_{j=1}^{J}\{(\bar{u}_{ij} - u_{ij})^2 + (\bar{v}_{ij} - v_{ij})^2 + (\bar{w}_{ij} - w_{ij})^2\}$$

j : Node J : Number of nodes

i : Node in time I : Number of nodes in time

$\bar{u}_{ij}, \bar{v}_{ij}, \bar{w}_{ij}$ **: Measured displacements in x,y,z**

u_{ij}, v_{ij}, w_{ij} **: Computed displacements in x,y,z**

$U_n = 0$ → **Damaged components and their damage levels are identified.**

Searching Minimal Value of Evaluation Function

		Factors						
		1	2	⋯	l	⋯	L	U_n
Data numbers	1	k_{11}	k_{12}	⋯	k_{1l}	⋯	k_{1L}	U_1
	2	k_{21}	k_{22}	⋯	k_{2l}	⋯	k_{2L}	U_2
	⋮	⋮	⋮		⋮		⋮	⋮
	n	k_{n1}	k_{n2}	⋯	k_{nl}	⋯	k_{nL}	U_n
	⋮	⋮	⋮		⋮		⋮	⋮
	N	k_{N1}	k_{N2}	⋯	k_{Nl}	⋯	k_{NL}	U_N
		S_{11}	S_{12}	⋯	S_{1l}	⋯	S_{1L}	
		⋮	⋮		⋮		⋮	
	S_{kl}	S_{k1}	S_{k2}	⋯	S_{kl}	⋯	S_{kL}	
		⋮	⋮		⋮		⋮	
		S_{K1}	S_{K2}	⋯	S_{Kl}	⋯	S_{KL}	

S_{kl}: Sum of U_n in factor l under damage level k

$$S_{kl} = \sum_n U_n(k,l)$$

Search for minimum S_{kl}

Damaged components and their levels are estimated.

Comparison of Evaluation Function

		Factors						
		1	2	⋯	l	⋯	L	U_n
Data numbers	1	k_{11}	k_{12}	⋯	k_{1l}	⋯	k_{1L}	U_1
	2	k_{21}	k_{22}	⋯	k_{2l}	⋯	k_{2L}	U_2
	⋮	⋮	⋮		⋮		⋮	⋮
	n	k_{n1}	k_{n2}	⋯	k_{nl}	⋯	k_{nL}	U_n
	⋮	⋮	⋮		⋮		⋮	⋮
	N	k_{N1}	k_{N2}	⋯	k_{Nl}	⋯	k_{NL}	U_N
		S_{11}	S_{12}	⋯	S_{1l}	⋯	S_{1L}	
		⋮	⋮		⋮		⋮	
	S_{kl}	S_{k1}	S_{k2}	⋯	S_{kl}	⋯	S_{kL}	
		⋮	⋮		⋮		⋮	
		S_{K1}	S_{K2}	⋯	S_{Kl}	⋯	S_{KL}	

Search for minimum S_{kl}

Damage level k_{nl} is fixed

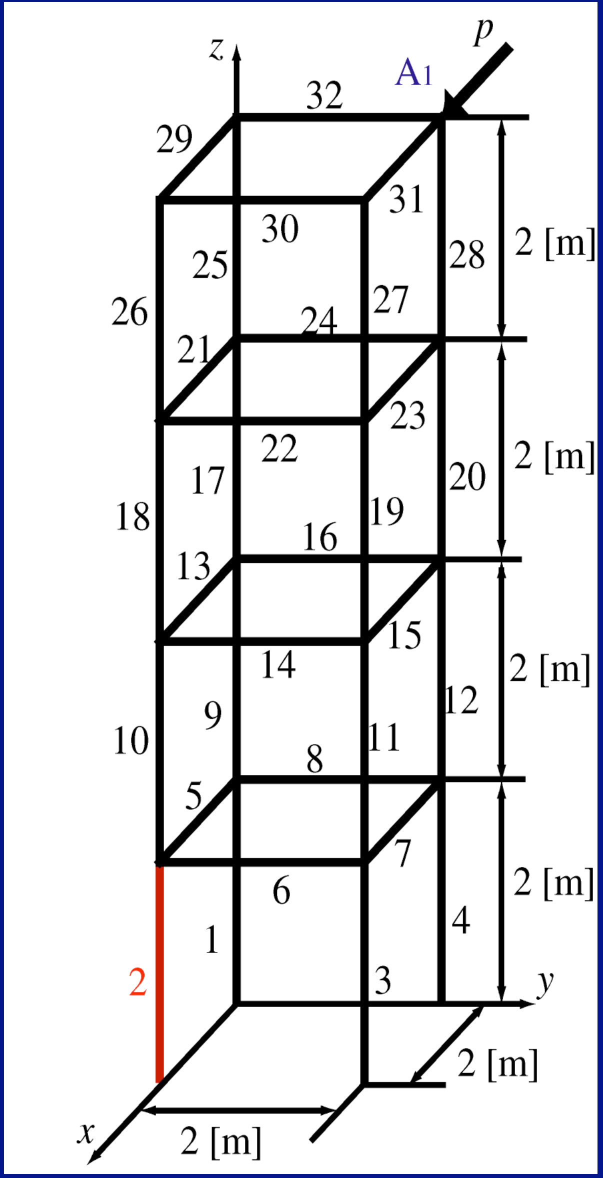
Search for the structure providing minimum U_n

Damaged components and their levels are identified.

Flow of Analysis

Step 1	Determine factors and levels based on a priori information
Step 2	Input measured data
Step 3	Obtain computed data for damaged models of structure
Step 4	Compute squared sum of measured and computed results
Step 5	Estimate the damaged components and their damage levels
Step 6	Carry out Steps 3 to 5 for all components of the structure
Step 7	Carry out Steps 3 to 5 for doubtful components of damage
Step 8	Iterate Step 7 until the final estimation is obtained
Step 9	Output the final results

Example 1



Member 2 : Young's modulus 50%

Structure:

Bottom is clamped to the plane *xy*

Each member has the same circular cross-section with radius 0.01[m]

Material constants:

Young's modulus $E = 210$ [GPa]

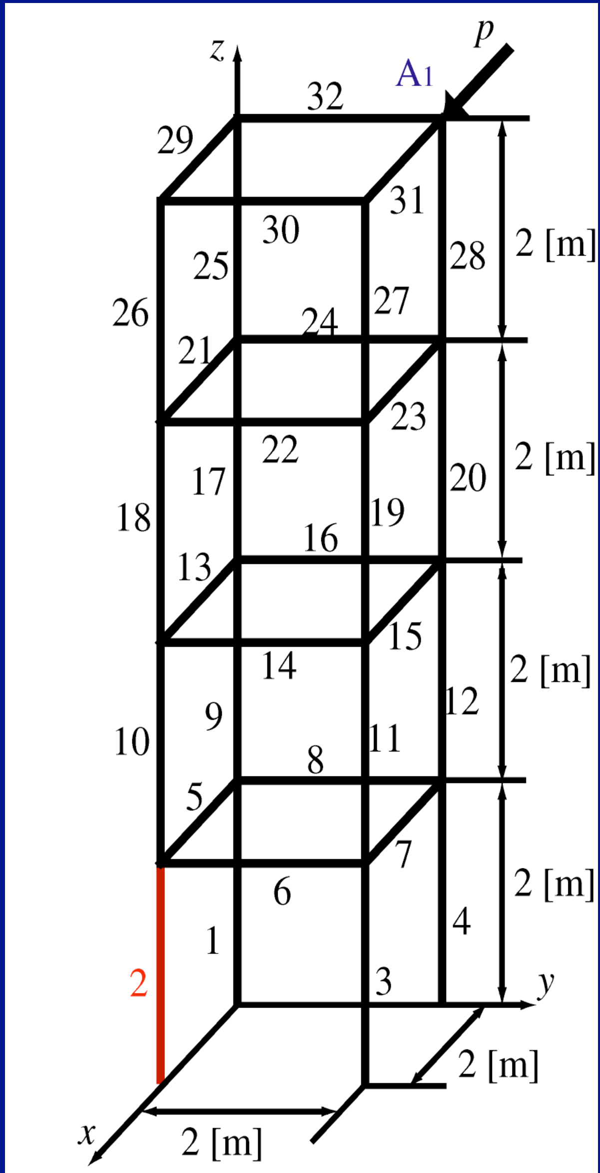
Density $\rho = 7860$ [kg/m^3]

Poisson's ratio $\nu = 0.3$

Concentrated load $P = 100H(t)$ [N] is applied to point A_1 along the axis x for 0.5 [s]. The displacements in x and y directions are measured for 2.0[s] at equal 10 steps.

Example 1

Member 2 : Young's modulus 50%

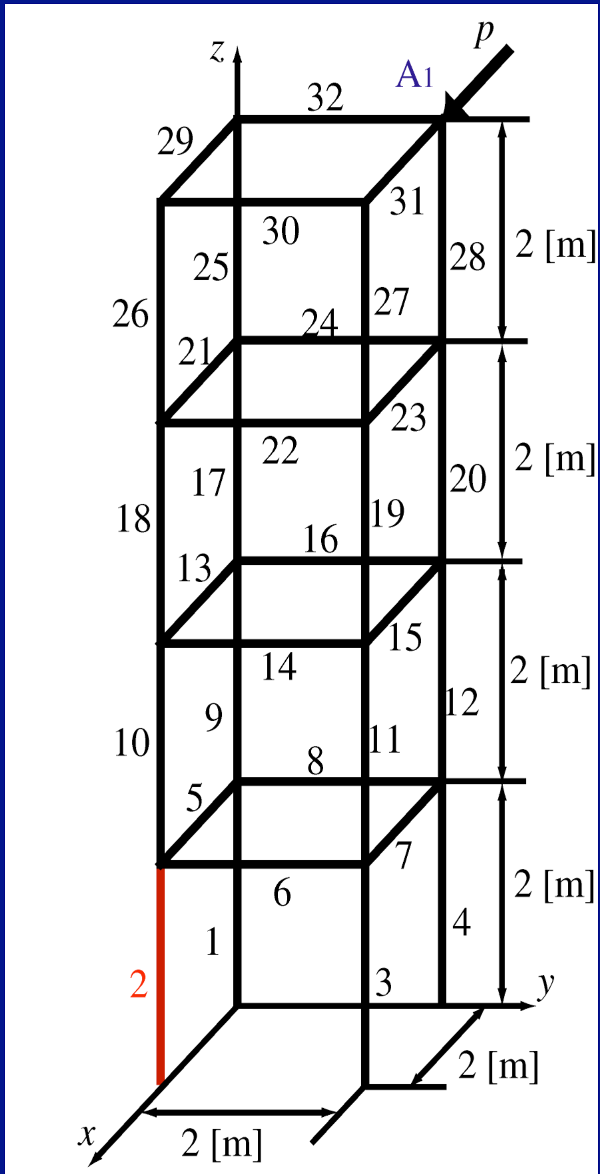


Orthogonal Table

	Member 1	Member 2	Member 3	Member 4	U_n
No.1	100%	100%	100%	100%	3.387E- 04
No.2	100%	50%	50%	50%	1.687E- 02
No.3	100%	25%	25%	25%	7.888E- 02
No.4	50%	100%	50%	25%	5.093E- 02
No.5	50%	50%	25%	100%	9.439E- 03
No.6	50%	25%	100%	50%	4.765E- 03
No.7	25%	100%	25%	50%	4.926E- 02
No.8	25%	50%	100%	25%	1.943E- 02
No.9	25%	25%	50%	100%	5.910E- 03
S_{1l}	9.608E- 02	1.005E- 01	2.454E- 02	1.569E- 02	
S_{2l}	6.514E- 02	4.574E- 02	7.371E- 02	7.089E- 02	
S_{3l}	7.460E- 02	8.955E- 02	1.376E- 01	1.492E- 01	

Example 1

Member 2 : Young's modulus 50%

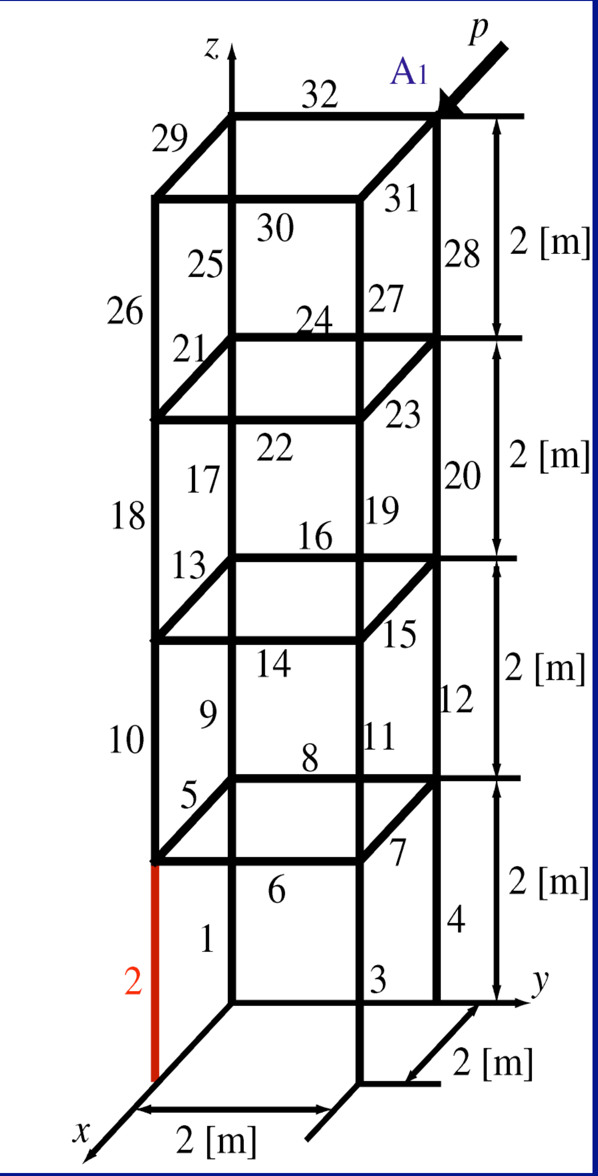


Orthogonal Table

	Member 1	Member 2	Member 3	Member 4	U_n
No.1	100%	100%	100%	100%	3.387E- 04
No.2	100%	50%	50%	100%	2.620E- 03
No.3	100%	25%	25%	100%	9.183E- 03
No.4	50%	100%	50%	100%	3.751E- 03
No.5	50%	50%	25%	100%	9.439E- 03
No.6	50%	25%	100%	100%	8.764E- 04
No.7	25%	100%	25%	100%	1.192E- 02
No.8	25%	50%	100%	100%	7.720E- 04
No.9	25%	25%	50%	100%	5.910E- 03
S_{1l}	1.214E- 02	1.601E- 02	1.987E- 03		
S_{2l}	1.407E- 02	1.283E- 02	1.228E- 02		
S_{3l}	1.861E- 02	1.597E- 02	3.055E- 02		

Example 1

Member 2 : Young's modulus 50%

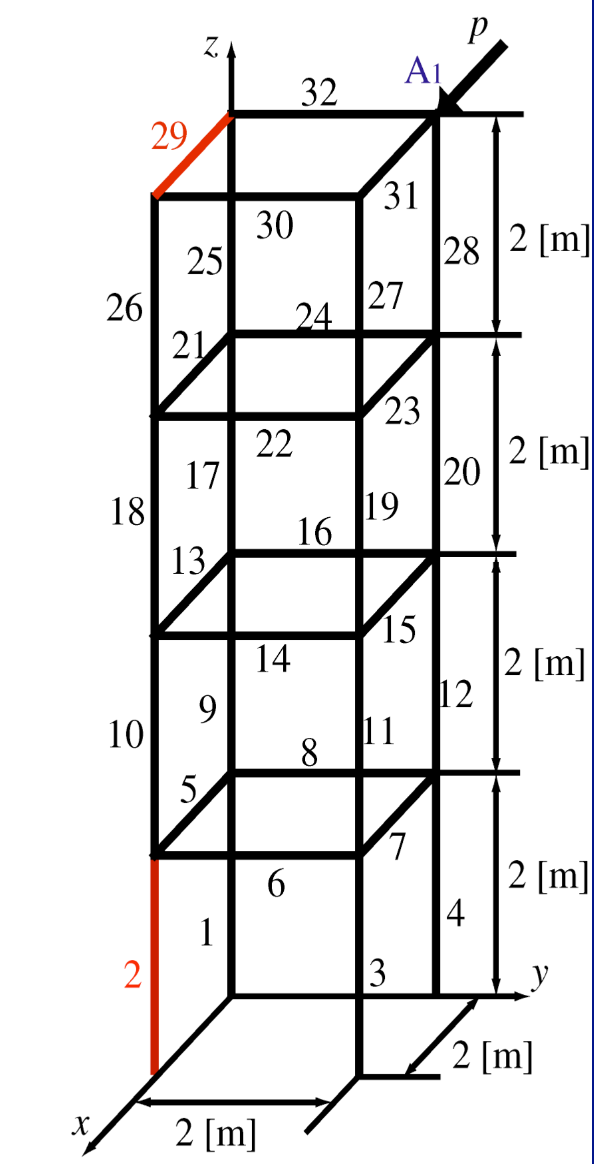


Orthogonal Table

	Member 1	Member 2	Member 3	Member 4	U_n
No.1	100%	100%	100%	100%	3.387E- 04
No.2	100%	50%	100%	100%	7.035E- 07
No.3	100%	25%	100%	100%	2.202E- 04
No.4	50%	100%	100%	100%	5.234E- 04
No.5	50%	50%	100%	100%	2.307E- 04
No.6	50%	25%	100%	100%	8.764E- 04
No.7	25%	100%	100%	100%	8.417E- 04
No.8	25%	50%	100%	100%	7.720E- 04
No.9	25%	25%	100%	100%	4.872E- 02
S_{1l}	5.595E- 04	1.704E- 03			
S_{2l}	1.630E- 03	1.003E- 03			
S_{3l}	3.609E- 03	3.092E- 03			

Example 2

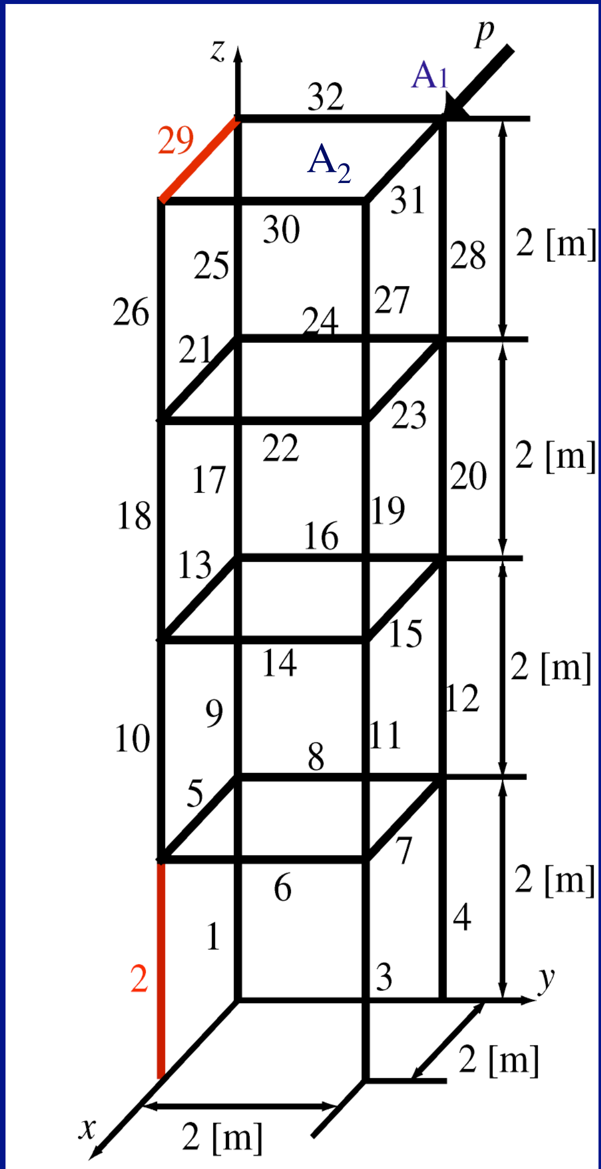
Member 2 : Young's modulus 50%
Member 29 : Young's modulus 25%



Member	Exact	Analysis
1	100 %	25 %
2	50 %	25 %
3	100 %	100 %
4	100 %	100 %
5	100 %	50 %
6	100 %	100 %
7	100 %	100 %
8	100 %	100 %
9	100 %	100 %
10	100 %	100 %
11	100 %	100 %
12	100 %	50 %
13	100 %	100 %
14	100 %	100 %
15	100 %	100 %
16	100 %	100 %

Member	Exact	Analysis
17	100 %	25 %
18	100 %	100 %
19	100 %	100 %
20	100 %	100 %
21	100 %	50 %
22	100 %	100 %
23	100 %	100 %
24	100 %	100 %
25	100 %	25 %
26	100 %	25 %
27	100 %	100 %
28	100 %	100 %
29	25 %	25 %
30	100 %	100 %
31	100 %	100 %
32	100 %	100 %

Example 2

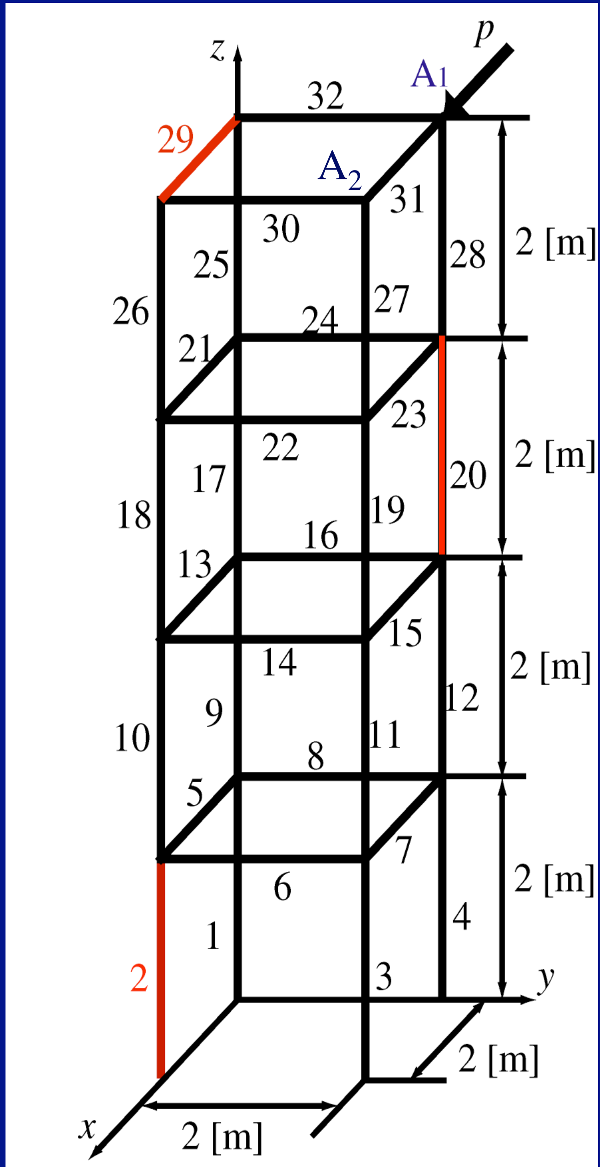


Final results

Member 2 : Young's modulus 50%
Member 29 : Young's modulus 25%

Doubtful components are again checked using the orthogonal table. Finally, it is estimated that the components 2 and 29 are damaged as into the assumed levels.

Example 3 Structure with damage different from the assumed damage level



Member 2 : Young's modulus 20%
Member 20 : Young's modulus 40%
Member 29 : Young's modulus 60%

Experimental design assumes the three levels 25%, 50% and 100%. We want to know what happens in such a case.

Example 3

Member 2 : Young's modulus 20%
Member 20 : Young's modulus 40%
Member 29 : Young's modulus 60%

1st trial (Node A_1):

Rod No.	Rigidity in %	Rod No.	Rigidity in %	Rod No.	Rigidity in %	Rod No.	Rigidity in %
1	100	9	100	17	100	25	100
2	25	10	100	18	100	26	100
3	100	11	100	19	100	27	100
4	100	12	100	20	25	28	100
5	100	13	100	21	100	29	25
6	100	14	100	22	100	30	100
7	100	15	100	23	100	31	100
8	100	16	100	24	100	32	100

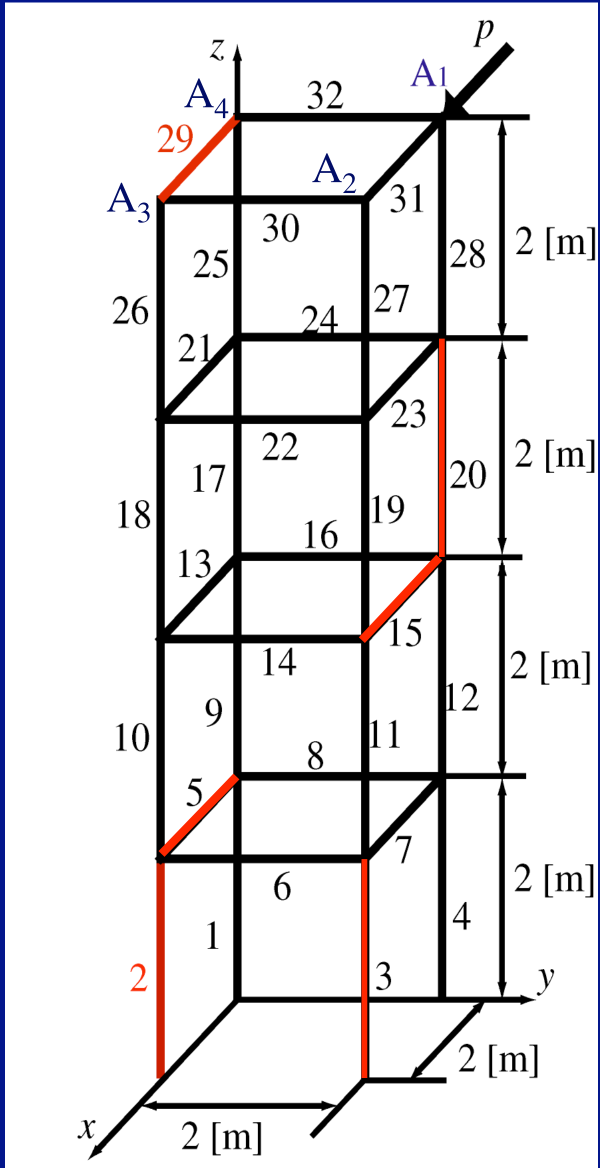
Example 3

Member 2 : Young's modulus 20%
Member 20 : Young's modulus 40%
Member 29 : Young's modulus 60%

2nd trial (Nodes A_1 and A_2):

Rod No.	Rigidity in %	Rod No.	Rigidity in %	Rod No.	Rigidity in %	Rod No.	Rigidity in %
1	100	9	100	17	100	25	100
2	25	10	100	18	100	26	100
3	100	11	100	19	100	27	100
4	100	12	100	20	50	28	100
5	100	13	100	21	100	29	50
6	100	14	100	22	100	30	100
7	100	15	100	23	100	31	100
8	100	16	100	24	100	32	100

Example 4 Structure with several damaged members with different levels from the assumed ones



Member 2 : Young's modulus 50%
Member 3 : Young's modulus 25%
Member 5 : Young's modulus 55%
Member 15 : Young's modulus 35%
Member 20 : Young's modulus 20%
Member 29 : Young's modulus 50%

Experimental design assumes the three levels 25%, 50% and 100%. We want to know what happens in this case.

Example 4

Member 2 : Young's modulus 50%
Member 3 : Young's modulus 25%
Member 5 : Young's modulus 55%
Member 15 : Young's modulus 35%
Member 20 : Young's modulus 20%
Member 29 : Young's modulus 50%

1st trial (Node A_1):

Rod No.	Rigidity in %	Rod No.	Rigidity in %	Rod No.	Rigidity in %	Rod No.	Rigidity in %
1	100	9	100	17	100	25	100
2	50	10	100	18	100	26	100
3	50	11	100	19	100	27	100
4	100	12	100	20	25	28	100
5	50	13	100	21	100	29	50
6	100	14	100	22	100	30	100
7	100	15	25	23	100	31	100
8	100	16	100	24	100	32	100

Example 4

Member 2 : Young's modulus 50%
Member 3 : Young's modulus 25%
Member 5 : Young's modulus 55%
Member 15 : Young's modulus 35%
Member 20 : Young's modulus 20%
Member 29 : Young's modulus 50%

2nd trial (Nodes A_1 to A_4):

Rod No.	Rigidity in %	Rod No.	Rigidity in %	Rod No.	Rigidity in %	Rod No.	Rigidity in %
1	100	9	100	17	100	25	100
2	50	10	100	18	100	26	100
3	25	11	100	19	100	27	100
4	100	12	100	20	25	28	100
5	50	13	100	21	100	29	50
6	100	14	100	22	100	30	100
7	100	15	25	23	100	31	100
8	100	16	100	24	100	32	100

Concluding Remarks

- Experimental design is very tough and robust for damage detection in frame structures.
- Damage detection can be done with a fewer number of points for measurement.
- Based on the estimated results by the present method we may improve the solutions via the sensitivity-based inverse analysis.