

Structural Matrices in *MDOF* Systems

Giacomo Boffi

Dipartimento di Ingegneria Strutturale, Politecnico di Milano

May 8, 2012

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Choice of
Property
Formulation

Outline

Introductory Remarks

Structural Matrices

Orthogonality Relationships

Additional Orthogonality Relationships

Evaluation of Structural Matrices

Flexibility Matrix

Example

Stiffness Matrix

Mass Matrix

Damping Matrix

Geometric Stiffness

External Loading

Choice of Property Formulation

Static Condensation

Example

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Choice of
Property
Formulation

Introductory Remarks

Today we will study the properties of structural matrices, that is the operators that relate the vector of system coordinates x and its time derivatives \dot{x} and \ddot{x} to the forces acting on the system nodes, f_S , f_D and f_I , respectively.

In the end, we will see again the solution of a *MDOF* problem by superposition, and in general today we will revisit many of the subjects of our previous class, but you know that a bit of reiteration is really good for developing minds.

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Choice of
Property
Formulation

Structural Matrices

We already met the mass and the stiffness matrix, M and K , and tangentially we introduced also the damping matrix C . We have seen that these matrices express the linear relation that holds between the vector of system coordinates x and its time derivatives \dot{x} and \ddot{x} to the forces acting on the system nodes, f_S , f_D and f_I , elastic, damping and inertial force vectors.

$$M \ddot{x} + C \dot{x} + K x = p(t)$$

$$f_I + f_D + f_S = p(t)$$

Also, we know that M and K are symmetric and definite positive, and that it is possible to uncouple the equation of motion expressing the system coordinates in terms of the *eigenvectors*, $x(t) = \sum q_i \psi_i$, where the q_i are the *modal coordinates* and the eigenvectors ψ_i are the non-trivial solutions to the characteristic equation,

$$(K - \omega^2 M) \psi = 0$$

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Orthogonality Relationships
Additional Orthogonality Relationships

Evaluation of Structural Matrices

Choice of Property Formulation

Free Vibrations

From the homogeneous, undamped problem

$$M \ddot{x} + K x = 0$$

introducing separation of variables

$$x(t) = \psi (A \sin \omega t + B \cos \omega t)$$

we wrote the homogeneous linear system

$$(K - \omega^2 M) \psi = 0$$

whose non-trivial solutions ψ_i for ω_i^2 such that $\|K - \omega_i^2 M\| = 0$ are the eigenvectors.

It was demonstrated that, for each pair of distinct *eigenvalues* ω_r^2 and ω_s^2 , the corresponding eigenvectors obey the orthogonality condition,

$$\psi_s^T M \psi_r = \delta_{rs} M_r, \quad \psi_s^T K \psi_r = \delta_{rs} \omega_r^2 M_r.$$

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Orthogonality Relationships
Additional Orthogonality Relationships

Evaluation of Structural Matrices

Choice of Property Formulation

Additional Orthogonality Relationships

From

$$K \psi_s = \omega_s^2 M \psi_s$$

premultiplying by $\psi_r^T K M^{-1}$ we have

$$\psi_r^T K M^{-1} K \psi_s = \omega_s^2 \psi_r^T K \psi_s = \delta_{rs} \omega_r^4 M_r,$$

premultiplying the first equation by $\psi_r^T K M^{-1} K M^{-1}$

$$\psi_r^T K M^{-1} K M^{-1} K \psi_s = \omega_s^2 \psi_r^T K M^{-1} K \psi_s = \delta_{rs} \omega_r^6 M_r$$

and, generalizing,

$$\psi_r^T (K M^{-1})^b K \psi_s = \delta_{rs} (\omega_r^2)^{b+1} M_r.$$

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Orthogonality Relationships
Additional Orthogonality Relationships

Evaluation of Structural Matrices

Choice of Property Formulation

Additional Relationships, 2

From

$$M \psi_s = \omega_s^{-2} K \psi_s$$

premultiplying by $\psi_r^T M K^{-1}$ we have

$$\psi_r^T M K^{-1} M \psi_s = \omega_s^{-2} \psi_r^T M \psi_s = \delta_{rs} \frac{M_s}{\omega_s^2}$$

premultiplying the first eq. by $\psi_r^T (M K^{-1})^2$ we have

$$\psi_r^T (M K^{-1})^2 M \psi_s = \omega_s^{-2} \psi_r^T M K^{-1} M \psi_s = \delta_{rs} \frac{M_s}{\omega_s^4}$$

and, generalizing,

$$\psi_r^T (M K^{-1})^b M \psi_s = \delta_{rs} \frac{M_s}{\omega_s^{2b}}$$

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Orthogonality
Relationships

Additional
Orthogonality
Relationships

Evaluation of
Structural
Matrices

Choice of
Property
Formulation

Additional Relationships, 3

Defining $X_{rs}(k) = \psi_r^T M (M^{-1} K)^k \psi_s$ we have

$$\begin{cases} X_{rs}(0) = \psi_r^T M \psi_s & = \delta_{rs} (\omega_s^2)^0 M_s \\ X_{rs}(1) = \psi_r^T K \psi_s & = \delta_{rs} (\omega_s^2)^1 M_s \\ X_{rs}(2) = \psi_r^T (K M^{-1}) K \psi_s & = \delta_{rs} (\omega_s^2)^2 M_s \\ \dots & \\ X_{rs}(n) = \psi_r^T (K M^{-1})^{n-1} K \psi_s & = \delta_{rs} (\omega_s^2)^n M_s \end{cases}$$

Observing that $(M^{-1} K)^{-1} = (K^{-1} M)^1$

$$\begin{cases} X_{rs}(-1) = \psi_r^T (M K^{-1}) M \psi_s & = \delta_{rs} (\omega_s^2)^{-1} M_s \\ \dots & \\ X_{rs}(-n) = \psi_r^T (M K^{-1})^n M \psi_s & = \delta_{rs} (\omega_s^2)^{-n} M_s \end{cases}$$

finally

$$X_{rs}(k) = \delta_{rs} \omega_s^{2k} M_s \quad \text{for } k = -\infty, \dots, \infty.$$

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Orthogonality
Relationships

Additional
Orthogonality
Relationships

Evaluation of
Structural
Matrices

Choice of
Property
Formulation

Flexibility

Given a system whose state is determined by the generalized displacements x_j of a set of nodes, we define the flexibility f_{jk} as the deflection, in direction of x_j , due to the application of a unit force in correspondance of the displacement x_k . The matrix $F = [f_{jk}]$ is the *flexibility matrix*.

The definition of flexibility put in clear that the degrees of freedom correspond to the points where there is a) application of external forces and/or b) presence of inertial forces.

Given a load vector $p = \{p_k\}$, the displacement x_j is

$$x_j = \sum f_{jk} p_k$$

or, in vector notation,

$$x = F p$$

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Flexibility Matrix

Example
Stiffness Matrix
Strain Energy
Symmetry

Direct
Assemblage

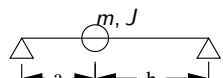
Example
Mass Matrix
Consistent Mass
Matrix

Discussion
Damping Matrix

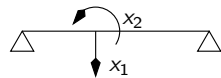
Example
Geometric
Stiffness
External Loading

Choice of
Property
Formulation

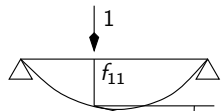
Example



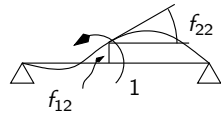
The dynamical system



The degrees of freedom



Displacements due to $p_1 = 1$



and due to $p_2 = 1$.

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Evaluation of Structural Matrices

Flexibility Matrix

Example

Stiffness Matrix

Strain Energy

Symmetry

Direct

Assemblage

Example

Mass Matrix

Consistent Mass Matrix

Discussion

Damping Matrix

Example

Geometric

Stiffness

External Loading

Choice of

Property

Formulation

Elastic Forces

Momentarily disregarding inertial effects, each node shall be in equilibrium under the action of the external forces and the elastic forces, hence taking into accounts all the nodes, all the external forces and all the elastic forces it is possible to write the vector equation of equilibrium

$$p = f_S$$

and, substituting in the previous vector expression of the displacements

$$x = F f_S$$

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Evaluation of Structural Matrices

Flexibility Matrix

Example

Stiffness Matrix

Strain Energy

Symmetry

Direct

Assemblage

Example

Mass Matrix

Consistent Mass Matrix

Discussion

Damping Matrix

Example

Geometric

Stiffness

External Loading

Choice of

Property

Formulation

Stiffness Matrix

The *stiffness matrix* K can be simply defined as the inverse of the flexibility matrix F ,

$$K = F^{-1}.$$

Alternatively the single coefficient k_{ij} can be defined as the external force (equal and opposite to the corresponding elastic force) applied to the *DOF* number i that gives place to a displacement vector $x^{(j)} = \{x_n\} = \{\delta_{nj}\}$, where all the components are equal to zero, except for $x_j^{(j)} = 1$. Collecting all the $x^{(j)}$ in a matrix X , it is $X = I$ and we have, writing all the equations at once,

$$X = I = F [k_{ij}], \Rightarrow [k_{ij}] = K = F^{-1}.$$

Finally,

$$p = f_S = K x.$$

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Evaluation of Structural Matrices

Flexibility Matrix

Example

Stiffness Matrix

Strain Energy

Symmetry

Direct

Assemblage

Example

Mass Matrix

Consistent Mass Matrix

Discussion

Damping Matrix

Example

Geometric

Stiffness

External Loading

Choice of

Property

Formulation

Strain Energy

The elastic strain energy V can be written in terms of displacements and external forces,

$$V = \frac{1}{2} \mathbf{p}^T \mathbf{x} = \frac{1}{2} \begin{cases} \mathbf{p}^T \mathbf{F} \mathbf{p}, \\ \mathbf{x}^T \mathbf{K} \mathbf{x}. \\ \mathbf{p}^T \end{cases}$$

Because the elastic strain energy of a stable system is always greater than zero, \mathbf{K} is a positive definite matrix. On the other hand, for an unstable system, think of a compressed beam, there are displacement patterns that are associated to zero strain energy.

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Flexibility Matrix
Example

Stiffness Matrix

Strain Energy

Symmetry

Direct
Assemblage
Example

Mass Matrix
Consistent Mass
Matrix

Discussion
Damping Matrix

Example

Geometric
Stiffness

External Loading

Choice of
Property
Formulation

Symmetry

Two sets of loads \mathbf{p}^A and \mathbf{p}^B are applied, one after the other, to an elastic system; the work done is

$$V_{AB} = \frac{1}{2} \mathbf{p}^{AT} \mathbf{x}^A + \mathbf{p}^{AT} \mathbf{x}^B + \frac{1}{2} \mathbf{p}^{BT} \mathbf{x}^B.$$

If we revert the order of application the work is

$$V_{BA} = \frac{1}{2} \mathbf{p}^{BT} \mathbf{x}^B + \mathbf{p}^{BT} \mathbf{x}^A + \frac{1}{2} \mathbf{p}^{AT} \mathbf{x}^A.$$

The total work being independent of the order of loading,

$$\mathbf{p}^{AT} \mathbf{x}^B = \mathbf{p}^{BT} \mathbf{x}^A.$$

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Flexibility Matrix
Example

Stiffness Matrix

Strain Energy

Symmetry

Direct
Assemblage
Example

Mass Matrix
Consistent Mass
Matrix

Discussion
Damping Matrix

Example

Geometric
Stiffness

External Loading

Choice of
Property
Formulation

Symmetry, 2

Expressing the displacements in terms of \mathbf{F} ,

$$\mathbf{p}^{AT} \mathbf{F} \mathbf{p}^B = \mathbf{p}^{BT} \mathbf{F} \mathbf{p}^A,$$

both terms are scalars so we can write

$$\mathbf{p}^{AT} \mathbf{F} \mathbf{p}^B = \left(\mathbf{p}^{BT} \mathbf{F} \mathbf{p}^A \right)^T = \mathbf{p}^{AT} \mathbf{F}^T \mathbf{p}^B.$$

Because this equation holds for every \mathbf{p} , we conclude that

$$\mathbf{F} = \mathbf{F}^T.$$

The inverse of a symmetric matrix is symmetric, hence

$$\mathbf{K} = \mathbf{K}^T.$$

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Flexibility Matrix
Example

Stiffness Matrix

Strain Energy

Symmetry

Direct
Assemblage
Example

Mass Matrix
Consistent Mass
Matrix

Discussion
Damping Matrix

Example

Geometric
Stiffness

External Loading

Choice of
Property
Formulation

Exceptions or not	Structural Matrices
<p>For the kind of <i>structures</i> we mostly deal with in our examples, problems, exercises and assignments, that is <i>simple structures</i>, it is usually convenient to compute the flexibility matrix applying the Principle of Virtual Displacements (we have seen an example last week) and inverting the flexibility to obtain the stiffness matrix, $K = F^{-1}$.</p> <p>For general structures, large and/or complex, the PVD approach cannot work in practice, as the number of degrees of freedom necessary to model the structural behaviour exceed our ability to do pencil and paper computations... Different methods are required to construct the stiffness matrix for such large, complex structures. Enters the Finite Element Method.</p>	Giacomo Boffi
	Introductory Remarks
	Structural Matrices
	Evaluation of Structural Matrices
	Flexibility Matrix Example
	Stiffness Matrix
	Strain Energy Symmetry
	Direct Assemblage
	Example
	Mass Matrix
Consistent Mass Matrix	
Discussion	
Damping Matrix	
Example	
Geometric Stiffness	
External Loading	
Choice of Property Formulation	

FEM	Structural Matrices
<p>The most common procedure to construct the matrices that describe the behaviour of a complex system is the <i>Finite Element Method</i>, or <i>FEM</i>. The procedure can be sketched in the following terms:</p> <ul style="list-style-type: none"> ▶ the structure is subdivided in non-overlapping portions, the <i>finite elements</i>, bounded by <i>nodes</i>, connected by the same nodes, ▶ the state of the structure can be described in terms of a vector x of generalized <i>nodal displacements</i>, ▶ there is a mapping between element and structure <i>DOF</i>'s, $i_{el} \mapsto r$, ▶ the <i>element stiffness matrix</i>, K_{el} establishes a linear relation between an element nodal displacements and forces, ▶ for each <i>FE</i>, all local k_{ij}'s are contributed to the global stiffness k_{rs}'s, with $i \mapsto r$ and $j \mapsto s$, taking in due consideration differences between local and global systems of reference. <p>Note that in the r-th <i>global</i> equation of equilibrium we have internal forces caused by the nodal displacements of the <i>FE</i> that have nodes i_{el} such that $i_{el} \mapsto r$, thus implying that global K is a <i>banded</i> matrix.</p>	Giacomo Boffi
	Introductory Remarks
	Structural Matrices
	Evaluation of Structural Matrices
	Flexibility Matrix Example
	Stiffness Matrix
	Strain Energy Symmetry
	Direct Assemblage
	Example
	Mass Matrix
Consistent Mass Matrix	
Discussion	
Damping Matrix	
Example	
Geometric Stiffness	
External Loading	
Choice of Property Formulation	

Example	Structural Matrices
<p>Consider a 2-D inextensible beam element, that has 4 <i>DOF</i>, namely two transverse end displacements x_1, x_2 and two end rotations, x_3, x_4. The element stiffness is computed using 4 shape functions ϕ_i, the transverse displacement being $v(s) = \sum_i \phi_i(s)x_i$, the different ϕ_i are such all end displacements or rotation are zero, except the one corresponding to index i.</p> <p>The shape functions for a beam are</p> $\phi_1(s) = 1 - 3\left(\frac{s}{L}\right)^2 + 2\left(\frac{s}{L}\right)^3, \quad \phi_2(s) = 3\left(\frac{s}{L}\right)^2 - 2\left(\frac{s}{L}\right)^3,$ $\phi_3(s) = s\left(1 - \left(\frac{s}{L}\right)^2\right), \quad \phi_4(s) = s\left(\left(\frac{s}{L}\right)^2 - \left(\frac{s}{L}\right)\right).$	Giacomo Boffi
	Introductory Remarks
	Structural Matrices
	Evaluation of Structural Matrices
	Flexibility Matrix Example
	Stiffness Matrix
	Strain Energy Symmetry
	Direct Assemblage
	Example
	Mass Matrix
Consistent Mass Matrix	
Discussion	
Damping Matrix	
Example	
Geometric Stiffness	
External Loading	
Choice of Property Formulation	

Example, 2

The element stiffness coefficients can be computed using, what else, the PVD: we compute the external virtual work done by a variation δx_i by the force due to a unit displacement x_j , that is k_{ij} ,

$$\delta W_{\text{ext}} = \delta x_i k_{ij},$$

the virtual internal work is the work done by the variation of the curvature, $\delta x_i \phi_i''(s)$ by the bending moment associated with a unit x_j , $\phi_j''(s) EJ(s)$,

$$\delta W_{\text{int}} = \int_0^L \delta x_i \phi_i''(s) \phi_j''(s) EJ(s) ds.$$

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Flexibility Matrix
Example
Stiffness Matrix
Strain Energy
Symmetry
Direct
Assemblage

Example
Mass Matrix
Consistent Mass
Matrix
Discussion
Damping Matrix
Example
Geometric
Stiffness
External Loading

Choice of
Property
Formulation

Example, 3

The equilibrium condition is the equivalence of the internal and external virtual works, so that simplifying δx_i we have

$$k_{ij} = \int_0^L \phi_i''(s) \phi_j''(s) EJ(s) ds.$$

For $EJ = \text{const}$,

$$\mathbf{f}_S = \frac{2EJ}{L^3} \begin{bmatrix} 6 & 6 & 3L & 3L \\ 6 & 6 & -3L & -3L \\ 3L & -3L & 2L^2 & L^2 \\ 3L & -3L & L^2 & 2L^2 \end{bmatrix} \mathbf{x}$$

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

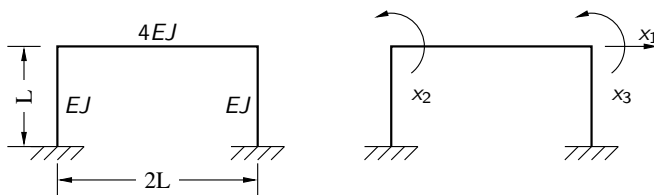
Evaluation of
Structural
Matrices

Flexibility Matrix
Example
Stiffness Matrix
Strain Energy
Symmetry
Direct
Assemblage

Example
Mass Matrix
Consistent Mass
Matrix
Discussion
Damping Matrix
Example
Geometric
Stiffness
External Loading

Choice of
Property
Formulation

Blackboard Time!



Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Flexibility Matrix
Example
Stiffness Matrix
Strain Energy
Symmetry
Direct
Assemblage

Example
Mass Matrix
Consistent Mass
Matrix
Discussion
Damping Matrix
Example
Geometric
Stiffness
External Loading

Choice of
Property
Formulation

Mass Matrix

The mass matrix maps the nodal accelerations to nodal inertial forces, and the most common assumption is to concentrate all masses in nodal point masses, without rotational inertia, computed *lumping* a fraction of each element mass (or a fraction of the supported mass) on all its bounding nodes.

This procedure leads to a so called *lumped* mass matrix, a diagonal matrix with diagonal elements greater than zero for all the translational degrees of freedom, and diagonal elements equal to zero for angular degrees of freedom.

The mass matrix is definite positive *only* if all the structure *DOF*'s are translational degrees of freedom, otherwise M is semi-definite positive and the eigenvalue procedure is not directly applicable. This problem can be overcome either by using a *consistent* mass matrix or using the *static condensation* procedure.

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Flexibility Matrix
Example

Stiffness Matrix
Strain Energy
Symmetry
Direct
Assemblage
Example

Mass Matrix
Consistent Mass
Matrix
Discussion
Damping Matrix
Example
Geometric
Stiffness
External Loading

Choice of
Property
Formulation

Consistent Mass Matrix

A consistent mass matrix is built using the rigorous *FEM* procedure, computing the nodal reactions that equilibrate the distributed inertial forces that develop in the element due to a linear combination of inertial forces.

Using our beam example as a reference, consider the inertial forces associated with a single nodal acceleration \ddot{x}_j , $f_{i,j}(s) = m(s)\phi_j(s)\ddot{x}_j$ and denote with $m_{ij}\ddot{x}_j$ the reaction associated with the i -nth degree of freedom of the element, by the PVD

$$\delta x_i m_{ij} \ddot{x}_j = \int \delta x_i \phi_i(s) m(s) \phi_j(s) ds \ddot{x}_j$$

simplifying

$$m_{ij} = \int m(s) \phi_i(s) \phi_j(s) ds.$$

For $m(s) = \bar{m} = \text{const.}$

$$f_1 = \frac{\bar{m}L}{420} \begin{bmatrix} 156 & 54 & 22L & -13L \\ 54 & 156 & 13L & -22L \\ 22L & 13L & 4L^2 & -3L^2 \\ -13L & -22L & -3L^2 & 4L^2 \end{bmatrix} \ddot{x}$$

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Flexibility Matrix
Example

Stiffness Matrix
Strain Energy
Symmetry
Direct
Assemblage
Example

Mass Matrix
Consistent Mass
Matrix
Discussion
Damping Matrix
Example
Geometric
Stiffness
External Loading

Choice of
Property
Formulation

Consistent Mass Matrix, 2

Pro

- ▶ some convergence theorem of *FEM* theory holds only if the mass matrix is consistent,
- ▶ slightly more accurate results,
- ▶ no need for static condensation.

Contra

- ▶ M is no more diagonal, heavy computational aggravation,
- ▶ static condensation is computationally beneficial, inasmuch it *reduces* the global number of degrees of freedom.

Structural
Matrices

Giacomo Boffi

Introductory
Remarks

Structural
Matrices

Evaluation of
Structural
Matrices

Flexibility Matrix
Example

Stiffness Matrix
Strain Energy
Symmetry
Direct
Assemblage
Example

Mass Matrix
Consistent Mass
Matrix
Discussion
Damping Matrix
Example
Geometric
Stiffness
External Loading

Choice of
Property
Formulation

Damping Matrix	Structural Matrices
<p>For each element $c_{ij} = \int c(s)\phi_i(s)\phi_j(s) ds$ and the damping matrix \mathbf{C} can be assembled from element contributions. However, using the FEM $\mathbf{C}^* = \mathbf{\Psi}^T \mathbf{C} \mathbf{\Psi}$ is not diagonal and the modal equations are uncoupled!</p> <p>The alternative is to write directly the global damping matrix, in terms of the underdetermined coefficients c_b,</p> $\mathbf{C} = \sum_b c_b \mathbf{M} (\mathbf{M}^{-1} \mathbf{K})^b .$	Giacomo Boffi
	Introductory Remarks
	Structural Matrices
	Evaluation of Structural Matrices
	Flexibility Matrix Example
	Stiffness Matrix
	Strain Energy Symmetry
	Direct Assemblage Example
	Mass Matrix
	Consistent Mass Matrix
	Discussion
	Damping Matrix
	Example
Geometric Stiffness	
External Loading	
Choice of Property Formulation	

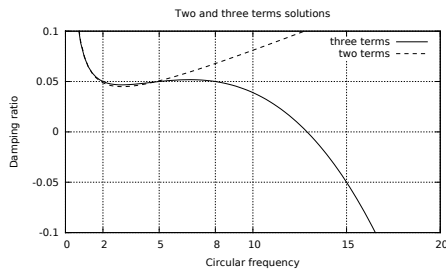
Damping Matrix	Structural Matrices
<p>With our definition of \mathbf{C},</p> $\mathbf{C} = \sum_b c_b \mathbf{M} (\mathbf{M}^{-1} \mathbf{K})^b ,$ <p>assuming normalized eigenvectors, we can write the individual component of $\mathbf{C}^* = \mathbf{\Psi}^T \mathbf{C} \mathbf{\Psi}$</p> $c_{ij}^* = \mathbf{\psi}_i^T \mathbf{C} \mathbf{\psi}_j = \delta_{ij} \sum_b c_b \omega_j^{2b}$ <p>due to the additional orthogonality relations, we recognize that now \mathbf{C}^* is a diagonal matrix.</p> <p>Introducing the modal damping C_j we have</p> $C_j = \mathbf{\psi}_j^T \mathbf{C} \mathbf{\psi}_j = \sum_b c_b \omega_j^{2b} = 2\zeta_j \omega_j$ <p>and we can write a system of linear equations in the c_b.</p>	Giacomo Boffi
	Introductory Remarks
	Structural Matrices
	Evaluation of Structural Matrices
	Flexibility Matrix Example
	Stiffness Matrix
	Strain Energy Symmetry
	Direct Assemblage Example
	Mass Matrix
	Consistent Mass Matrix
	Discussion
	Damping Matrix
	Example
Geometric Stiffness	
External Loading	
Choice of Property Formulation	

Example	Structural Matrices
<p>We want a fixed, 5% damping ratio for the first three modes, taking note that the modal equation of motion is</p> $\ddot{q}_i + 2\zeta_i \omega_i \dot{q}_i + \omega_i^2 q_i = p_i^*$ <p>Using</p> $\mathbf{C} = c_0 \mathbf{M} + c_1 \mathbf{K} + c_2 \mathbf{K} \mathbf{M}^{-1} \mathbf{K}$ <p>we have</p> $2 \times 0.05 \begin{Bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{Bmatrix} = \begin{bmatrix} 1 & \omega_1^2 & \omega_1^4 \\ 1 & \omega_2^2 & \omega_2^4 \\ 1 & \omega_3^2 & \omega_3^4 \end{bmatrix} \begin{Bmatrix} c_0 \\ c_1 \\ c_2 \end{Bmatrix}$ <p>Solving for the c's and substituting above, the resulting damping matrix is orthogonal to every eigenvector of the system, for the first three modes, leads to a modal damping ratio that is equal to 5%.</p>	Giacomo Boffi
	Introductory Remarks
	Structural Matrices
	Evaluation of Structural Matrices
	Flexibility Matrix Example
	Stiffness Matrix
	Strain Energy Symmetry
	Direct Assemblage Example
	Mass Matrix
	Consistent Mass Matrix
	Discussion
	Damping Matrix
	Example
Geometric Stiffness	
External Loading	
Choice of Property Formulation	

Example

Computing the coefficients c_0 , c_1 and c_2 to have a 5% damping at frequencies $\omega_1 = 2$, $\omega_2 = 5$ and $\omega_3 = 8$ we have $c_0 = 1200/9100$, $c_1 = 159/9100$ and $c_2 = -1/9100$.

Writing $\zeta(\omega) = \frac{1}{2} \left(\frac{c_0}{\omega} + c_1\omega + c_2\omega^3 \right)$ we can plot the above function, along with its two term equivalent ($c_0 = 10/70$, $c_1 = 1/70$).



Negative damping? No, thank you: use only an even number of terms.

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Evaluation of Structural Matrices

Flexibility Matrix Example

Stiffness Matrix

Strain Energy

Symmetry

Direct Assemblage

Example

Mass Matrix

Consistent Mass Matrix

Discussion

Damping Matrix

Example

Geometric Stiffness

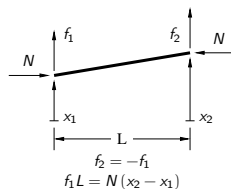
External Loading

Choice of Property Formulation

Geometric Stiffness

A common assumption is based on a linear approximation, for a beam element

$$\mathbf{f}_G = \frac{N}{L} \begin{bmatrix} +1 & -1 & 0 & 0 \\ -1 & +1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \mathbf{x}$$



It is possible to compute the geometrical stiffness matrix using *FEM*, shape functions and PVD,

$$k_{G,ij} = \int N(s)\phi'_i(s)\phi'_j(s) ds,$$

for constant N

$$\mathbf{K}_G = \frac{N}{30L} \begin{bmatrix} 36 & -36 & 3L & 3L \\ -36 & 36 & -3L & -3L \\ 3L & -3L & 4L^2 & -L^2 \\ 3L & -3L & -L^2 & 4L^2 \end{bmatrix}$$

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Evaluation of Structural Matrices

Flexibility Matrix Example

Stiffness Matrix

Strain Energy

Symmetry

Direct Assemblage

Example

Mass Matrix

Consistent Mass Matrix

Discussion

Damping Matrix

Example

Geometric Stiffness

External Loading

Choice of Property Formulation

External Loadings

Following the same line of reasoning that we applied to find nodal inertial forces, by the PVD and the use of shape functions we have

$$p_i(t) = \int p(s, t)\phi_i(s) ds.$$

For a constant, uniform load $p(s, t) = \bar{p} = \text{const}$, applied on a beam element,

$$\mathbf{p} = \bar{p}L \left\{ \frac{1}{2} \quad \frac{1}{2} \quad \frac{L}{12} \quad -\frac{L}{12} \right\}^T$$

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Evaluation of Structural Matrices

Flexibility Matrix Example

Stiffness Matrix

Strain Energy

Symmetry

Direct Assemblage

Example

Mass Matrix

Consistent Mass Matrix

Discussion

Damping Matrix

Example

Geometric Stiffness

External Loading

Choice of Property Formulation

Choice of Property Formulation	<p style="text-align: center;">Structural Matrices</p> <p style="text-align: center;">Giacomo Boffi</p> <p>Introductory Remarks</p> <p>Structural Matrices</p> <p>Evaluation of Structural Matrices</p> <p style="background-color: #FFD700;">Choice of Property Formulation</p> <p style="background-color: #FFD700;">Static Condensation Example</p>
Simplified Approach	
Some structural parameter is approximated, only translational <i>DOF</i> 's are retained in dynamic analysis.	
Consistent Approach	
All structural parameters are computed according to the <i>FEM</i> , and all <i>DOF</i> 's are retained in dynamic analysis.	
<p>If we choose a simplified approach, we must use a procedure to remove unneeded structural <i>DOF</i>'s from the model that we use for the dynamic analysis.</p> <p>Enter the <i>Static Condensation Method</i>.</p>	

Static Condensation	<p style="text-align: center;">Structural Matrices</p> <p style="text-align: center;">Giacomo Boffi</p> <p>Introductory Remarks</p> <p>Structural Matrices</p> <p>Evaluation of Structural Matrices</p> <p>Choice of Property Formulation</p> <p style="background-color: #FFD700;">Static Condensation Example</p>
<p>We have, from a <i>FEM</i> analysis, a stiffness matrix that uses all nodal <i>DOF</i>'s, and from the lumped mass procedure a mass matrix were only translational (and maybe a few rotational) <i>DOF</i>'s are blessed with a non zero diagonal term. In this case, we can always rearrange and partition the displacement vector x in two subvectors: a) x_A, all the <i>DOF</i>'s that are associated with inertial forces and b) x_B, all the remaining <i>DOF</i>'s not associated with inertial forces.</p> $x = \{x_A \quad x_B\}^T$	

Static Condensation, 2	<p style="text-align: center;">Structural Matrices</p> <p style="text-align: center;">Giacomo Boffi</p> <p>Introductory Remarks</p> <p>Structural Matrices</p> <p>Evaluation of Structural Matrices</p> <p>Choice of Property Formulation</p> <p style="background-color: #FFD700;">Static Condensation Example</p>
<p>After rearranging the <i>DOF</i>'s, we must rearrange also the rows (equations) and the columns (force contributions) in the structural matrices, and eventually partition the matrices so that</p> $\begin{Bmatrix} f_I \\ 0 \end{Bmatrix} = \begin{bmatrix} M_{AA} & M_{AB} \\ M_{BA} & M_{BB} \end{bmatrix} \begin{Bmatrix} \ddot{x}_A \\ \ddot{x}_B \end{Bmatrix}$ $f_S = \begin{bmatrix} K_{AA} & K_{AB} \\ K_{BA} & K_{BB} \end{bmatrix} \begin{Bmatrix} x_A \\ x_B \end{Bmatrix}$ <p>with</p> $M_{BA} = M_{AB}^T = 0, \quad M_{BB} = 0, \quad K_{BA} = K_{AB}^T$ <p>Finally we rearrange the loadings vector and write...</p>	

Static Condensation, 3

... the equation of dynamic equilibrium,

$$\mathbf{p}_A = \mathbf{M}_{AA}\ddot{\mathbf{x}}_A + \mathbf{M}_{AB}\ddot{\mathbf{x}}_B + \mathbf{K}_{AA}\mathbf{x}_A + \mathbf{K}_{AB}\mathbf{x}_B$$

$$\mathbf{p}_B = \mathbf{M}_{BA}\ddot{\mathbf{x}}_A + \mathbf{M}_{BB}\ddot{\mathbf{x}}_B + \mathbf{K}_{BA}\mathbf{x}_A + \mathbf{K}_{BB}\mathbf{x}_B$$

The terms in red are zero, so we can simplify

$$\mathbf{M}_{AA}\ddot{\mathbf{x}}_A + \mathbf{K}_{AA}\mathbf{x}_A + \mathbf{K}_{AB}\mathbf{x}_B = \mathbf{p}_A$$

$$\mathbf{K}_{BA}\mathbf{x}_A + \mathbf{K}_{BB}\mathbf{x}_B = \mathbf{p}_B$$

solving for \mathbf{x}_B in the 2nd equation and substituting

$$\mathbf{x}_B = \mathbf{K}_{BB}^{-1}\mathbf{p}_B - \mathbf{K}_{BB}^{-1}\mathbf{K}_{BA}\mathbf{x}_A$$

$$\mathbf{p}_A - \mathbf{K}_{BB}^{-1}\mathbf{K}_{BA}\mathbf{p}_B = \mathbf{M}_{AA}\ddot{\mathbf{x}}_A + (\mathbf{K}_{AA} - \mathbf{K}_{AB}\mathbf{K}_{BB}^{-1}\mathbf{K}_{BA})\mathbf{x}_A$$

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Evaluation of Structural Matrices

Choice of Property Formulation

Static Condensation Example

Static Condensation, 4

Going back to the homogeneous problem, with obvious positions we can write

$$(\bar{\mathbf{K}} - \omega^2\bar{\mathbf{M}})\boldsymbol{\psi}_A = \mathbf{0}$$

but the $\boldsymbol{\psi}_A$ are only part of the structural eigenvectors, because in essentially every application we must consider also the other *DOF*'s, so we write

$$\boldsymbol{\psi}_i = \begin{Bmatrix} \boldsymbol{\psi}_{A,i} \\ \boldsymbol{\psi}_{B,i} \end{Bmatrix}, \text{ with } \boldsymbol{\psi}_{B,i} = \mathbf{K}_{BB}^{-1}\mathbf{K}_{BA}\boldsymbol{\psi}_{A,i}$$

Structural Matrices

Giacomo Boffi

Introductory Remarks

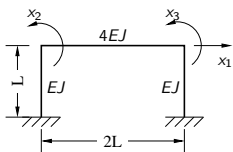
Structural Matrices

Evaluation of Structural Matrices

Choice of Property Formulation

Static Condensation Example

Example



$$\mathbf{K} = \frac{2EJ}{L^3} \begin{bmatrix} 12 & 3L & 3L \\ 3L & 6L^2 & 2L^2 \\ 3L & 2L^2 & 6L^2 \end{bmatrix}$$

Disregarding the factor $2EJ/L^3$,

$$\mathbf{K}_{BB} = L^2 \begin{bmatrix} 6 & 2 \\ 2 & 6 \end{bmatrix}, \mathbf{K}_{BB}^{-1} = \frac{1}{32L^2} \begin{bmatrix} 6 & -2 \\ -2 & 6 \end{bmatrix}, \mathbf{K}_{AB} = [3L \quad 3L]$$

The matrix $\bar{\mathbf{K}}$ is

$$\bar{\mathbf{K}} = \frac{2EJ}{L^3} (12 - \mathbf{K}_{AB}\mathbf{K}_{BB}^{-1}\mathbf{K}_{AB}^T) = \frac{39EJ}{2L^3}$$

Structural Matrices

Giacomo Boffi

Introductory Remarks

Structural Matrices

Evaluation of Structural Matrices

Choice of Property Formulation

Static Condensation Example