USER BULLETIN 8: DEEP BEAM MODELING WITH VECTOR5

APPLICABILITY

In the current implementation, the deep beam element is applicable for the cases where the end moments M1 and M2 have opposite signs or one of them is zero. In addition, the shear force must not change its sign during the analysis (i.e., no shear reversals).

DEEP BEAM DATA FILE

To perform an analysis with a model including a deep beam element, VecTor.DPBM file should be saved into the analysis folder with the following data.



To better understand these parameters, consider the simply supported deep beam shown below, subjected to three-point bending with two identical shear spans. *LB1* and *LB2* are the physical widths of the loading and supporting plates (or columns) of the element, respectively. The corresponding effective widths *LB1E* and *LB2E* are obtained from the following expression:

$$L_{b1(2)e} = \min\left[0.11\sqrt{a_{cl}^{2} + h^{2}}; \frac{V}{P_{1(2)}}L_{b1(2)}; 370 \, mm\right]$$

where:
 a_{cl} : clear shear span between adjacent point loads/support reactions
 h : member depth
 V : shear force in the shear span
 P_{1} : applied point load (at the top of the crack)
 P_{2} : support reaction (at the bottom of the crack)

In isolated statically determinate deep beams such as the beam shown below, the ratio $V/P_{1(2)}$ is determined from equilibrium only. In isolated statically indeterminate deep beams, $V/P_{1(2)}$ can be determined on the basis of a linear elastic analysis. If the deep beam is modelled as part of a frame structure where there are no clear loading plates and the columns can have moments in them, $V/P_{1(2)}$ can be estimated at 0.5. In all cases, if V/P exceeds 1, a value of 1 should be used.

For the shear spans under double curvature, note that the critical loading zone can occur at the bottom of the critical crack, and not at the top of the crack as assumed in this implementation of the deep beam element. Therefore, the results should be interpreted with caution when there are conditions for the CLZ to occur at the bottom of the crack. Refer to Liu and Mihaylov (2018) for more information.

As shown in the deep beam below, the nodes of the deep beam elements are located at the centers of the loading/supporting plates/columns. This is recommended when the width of the loading/supporting plates/columns LB1(2) is smaller than about 20% of the clear shear span. Otherwise, it is more appropriate to locate the end nodes at the ends of the clear shear span. In this case, the rectangular zones of intersection of the loading/supporting plates/columns with the deep beam should be modelled as rigid. FormWorks+ automated meshing algorithm is developed to consider both cases and create the mesh accordingly. The user should still carefully inspect the automatically generated mesh and make any necessary adjustments as needed.

To further illustrate the modelling of deep shear spans, consider the following examples of isolated deep beams, and deep beams in frame structures.



EXAMPLE 1: DEEP BEAM UNDER SYMMETRICAL THREE-POINT BENDING

EXAMPLE 2: DEEP BEAM UNDER UNSYMMETRICAL THREE-POINT BENDING

- Element 1, Node 1

$$L_{b2e} = min \left[0.11\sqrt{1600^2 + 1200^2}; 1 \times 200; 370 \ mm \right] = min [220; 200; 370 \ mm] = 200 \ mm$$

- Element 1, Node 2 $L_{b1e} = min \left[0.11\sqrt{1600^2 + 1200^2}; 0.538 \times 300; 370 \, mm \right] = min [220; 161; 370 \, mm] = 161 \, mm$
- Element 2, Node 1 $L_{b1e} = min \left[0.11\sqrt{1600^2 + 1200^2}; 0.463 \times 300; 370 \, mm \right] = min [220; 139; 370 \, mm] = 139 \, mm$



EXAMPLE 3: DEEP BEAM UNDER UNSYMMETRICAL FOUR-POINT BENDING





EXAMPLE 4: TWO-SPAN CONTINUOUS DEEP BEAM UNDER A POINT LOAD AT EACH SPAN

EXAMPLE 5: DEEP BEAM IN A FRAME STRUCTURE



FORMWORKS-PLUS MODELING

Each deep member section should be defined using the reference type 'deep beam' as shown below. The generation of the cross section and reinforcement details is the same as that for the slender members.

Define General Material Properties		>
Cross-Sections Type: Transfer Beam Add Section 1 Transfer Beam Delete Copy	Concrete Properties Deep Beam Reference Type: Deep Beam Section Type:	Transverse Reinforcing Bar Properties Transverse Reinf. Type: Closed Transverse Reinf. Bar Area: Select No. of Vertical Cross Ties: 0 No. of Horizontal Cross Ties: 0 Transverse Reinf. Spacing, St: 100 Transverse Reinf. Grade: Select

After the creation of all sections, auto-meshing function should be used in the same way as the slender- memberonly analysis. After meshing, identify the member numbers of every deep beam in the model. The sample frame shown below has two deep beam members with the numbers of 55 and 58. For each deep member, a line of input should be provided for the deep-beam specific parameters. FormWorks-Plus will use this input to create the deep beam data file (VecTor.DPBM) when you save the structure file. Use the icon at the top of the program screen (shown below) to open the input window. This window will have a line for each deep member with precalculated values. These values are calculated by pre-set algorithms which will not be entirely correct for all configurations of frame models. It is critical that the user calculates each of these values (as defined in this bulletin) and makes any necessary corrections. The rest of the modeling and analysis process is the same as that for slender members.



The shear crack direction has a major effect on the LB values to be input for each deep member. FWP makes the following assumption, which will only be valid for some configurations of frames. For a given deep beam element, FWP searches the frame for connecting columns at the top left, top right, bottom left, and bottom right. By default, FWP assumes a crack direction of 1. If it cannot detect a bottom left supporting column or support restraint, it assumes a crack direction of 2. The user should review and input the correct direction for each deep member. In the case of an uncertainty, the user should perform a preliminary analysis and review the crack directions in the post-processor Janus before making the final inputs.

OUTPUT FILES

The three parameters in each shear span (θ 1, θ 2 and Δ c) and four shear components (VCLZ, Vs, Vci and Vd) are recorded in '.A5E' files (output files) for each load step. The straight diagonal crack is described with its inclined angle, slip along the crack as well as the crack opening at the mid-length of the crack.

	DEEP BE ******	AM ELEMENT *******	RESULTS		
MOMENT1: MOMENT2: SHEAR:	-1.2 kN- 121.5 kN- -601.7 kN	т т т D	HETA1 HETA2 DELTAC	-0.00 0.25 2.52	milli-rad milli-rad mm
	SHEAR	RESISTANCE	FORCES		
VCLZ (KN)	V (K	S N)	VCI (KN)		VD (KN)
220.09	0.	00 2	19.49	1	.62.08
	CR 	ACK CONDITI	ONS		
ANGL (deg	E SLIP) (mm)	WCR A (m	\T H/2 1m)		
66.0	4 2.30	1.	05		

REFERENCES

Liu, J. and Mihaylov, B. I. (2018) "Macroelement for Complete Shear Behavior of Continuous Deep Beams." *ACI Structural Journal*, 115(4), pp. 1089-1099. <<u>web link</u>>

Liu, J., Guner, S., and Mihaylov, B. (2019) "Mixed-Type Modeling of Structures with Slender and Deep Beam Elements" *ACI Structural Journal*, 116(4), pp. 253-264.<<u>web link</u>>

Liu, J., Guner, S., and Mihaylov, B. (2021) "A New Deep-Beam Element for Mixed-Type Modeling of Concrete Structures," Project report, Collaborative study between the University of Toledo, USA, and University of Liège, Belgium, 31 pp. <<u>web link</u>>

Proestos, G., Palipana, D. and Mihaylov, B. I. (2021) "Evaluating the Shear Resistance of Deep Beams Loaded or Supported by Wide Elements." *Engineering Structures*, 226: 111368. <<u>web link</u>>

Bonus Material

A Macro-Element for the Nonlinear Analysis of RC Deep Beams based on a Three-Parameter Kinematic Theory

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fib Symposium 2016, Cape Town

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Structures with deep transfer girders





- Small shear-span-to-depth ratios (a/d ≤ approx. 2.5)
- **Complex deformation patterns** (plane sections do not remain plane)

Modelling of large structures with deep beams





Model with 1D frame elements

- Computationally efficient
- Inaccurate for deep beams



- Complex for large structures
- Suitable for deep beams

 \rightarrow Need for 1D element for deep beams combing simplicity and accuracy



Shear behaviour of continuous deep beams





(Mihaylov et al., 2015)

Three-parameter kinematic theory (3PKT) for deep beams







3PKT: **kinematics** + equilibrium + constitutive relationships for shear mechanisms

(Mihaylov et al., 2015)

Idea for macro element for deep beams





 $\theta_1 = \varepsilon_{t1} a/d$ $\theta_2 = \varepsilon_{t2} a/d$ $M_1(\theta_1) + M_2(\theta_2) = V(\Delta_c, \theta_1, \theta_2)a$

 \int

 $k_1\theta_1 + k_2\theta_2 = k_3\Delta_c a$ $k_1 = M_1/\theta_1$ $k_2 = M_2/\theta_2$ $k_3 = V/\Delta_c$

Rotational springs (flexural behaviour)







$$M \approx T(0.9d)$$

T is the tension in long. reinf.:

$$T = E_s A_s \varepsilon_t + \frac{0.33\sqrt{f_c}}{\sqrt{1+200\varepsilon_t}} A_{c,eff} \le A_s f_y$$
$$\varepsilon_t = \frac{\theta}{d} \frac{d}{a}$$

Transverse springs (shear behaviour)







Shear components from:

- V_{CLZ} critical loading zone
 - V_{ci} aggregate interlock
 - V_s stirrups
 - V_d dowel action

Springs of the four shear mechanisms





Stiffness matrix of macro element





Modelling of symmetrical simply supported beam tests



Specimens S1M/C

(Mihaylov et al., 2010)



Shear behaviour prediction of beams S1M/C





Observations from the full-beam modelling







Unloading path of shear mechanism springs





Shear behaviour prediction of beams S1M/C





Effect of aggregate interlock

Contact density model (Li et al., 1989)



Shear behaviour prediction of continuous deep beams





Specimens CDB1

(Mihaylov et al., 2015)

Full-beam model of CDB1





Shear behaviour prediction of continuous deep beams







Thank you!

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