Seminar "Implementarea în practica de proiectare anti-seismică din România a contravântuirilor cu flambaj împiedicat (IMSER)"

Analiza numerică și validarea experimentală a unor soluții de contravântuiri cu flambaj împiedicat

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- Introducere
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- Dezvoltare conceptuală
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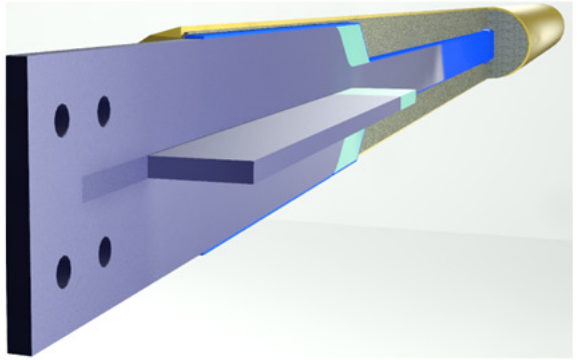
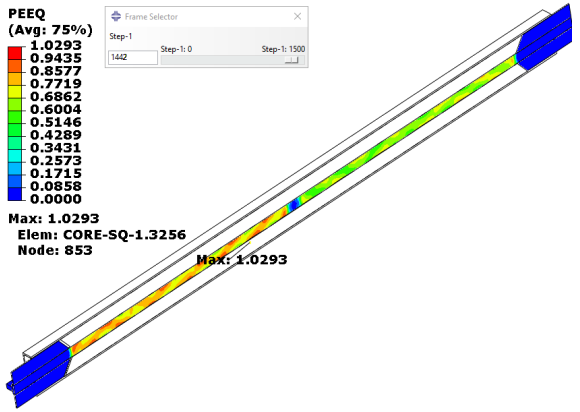
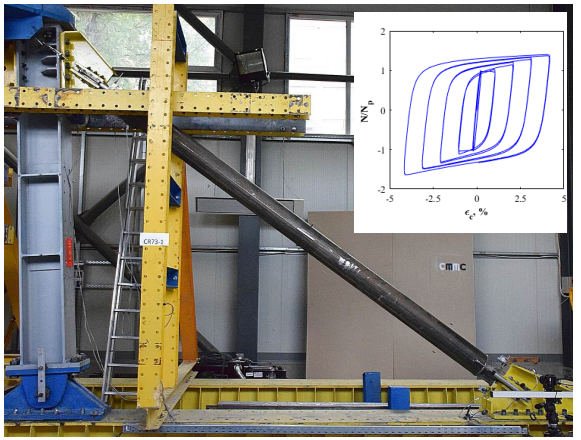
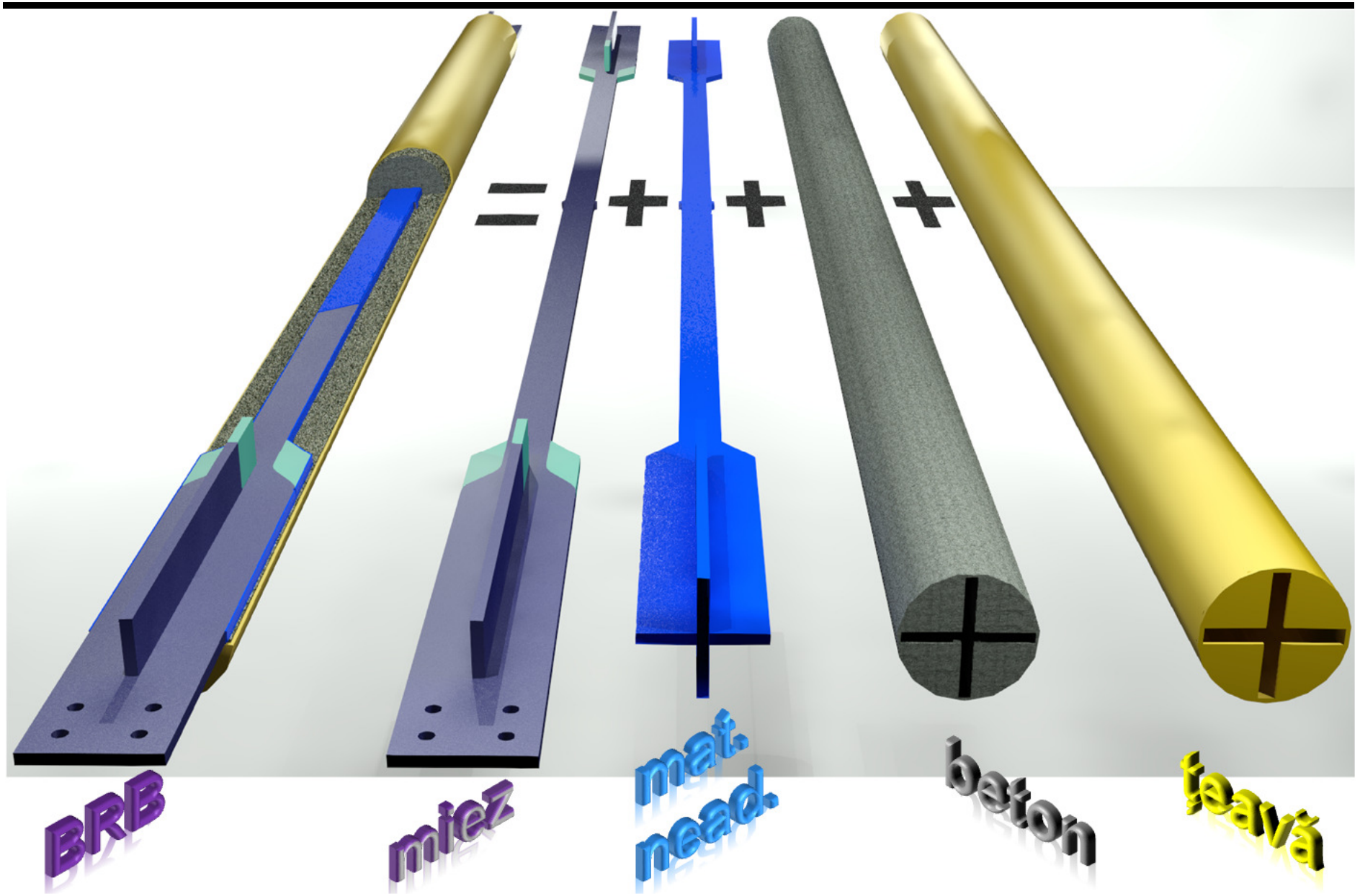






Introducere



Obiective

- **Dezvoltarea conceptuală a BRB bazată pe investigații numerice utilizând metoda elementului finit (MEF):**
  - **“conventional”;**
  - **“uscat”.**

- **Proiectarea soluțiilor inginerești ce urmează a fi încercate.**

- **Pretestări numerice (MEF) ale soluțiilor BRB finale.**

- **Încercări experimentale pe BRB-uri în vederea precalificării.**

Dezvoltarea conceptuală a BRB-urilor

Conceperea

S-a investigat:

- **Tehnologia de realizare a miezurilor:**
  - **din profile (platbandă, oțel pătrat/rotund) + table sudate**
  - **din table, prin prelucrare mecanică**

- **Soluția tehnică pentru zona de tranziție (cu racord, sudarea de rigidizări perpendiculare pe miez)**

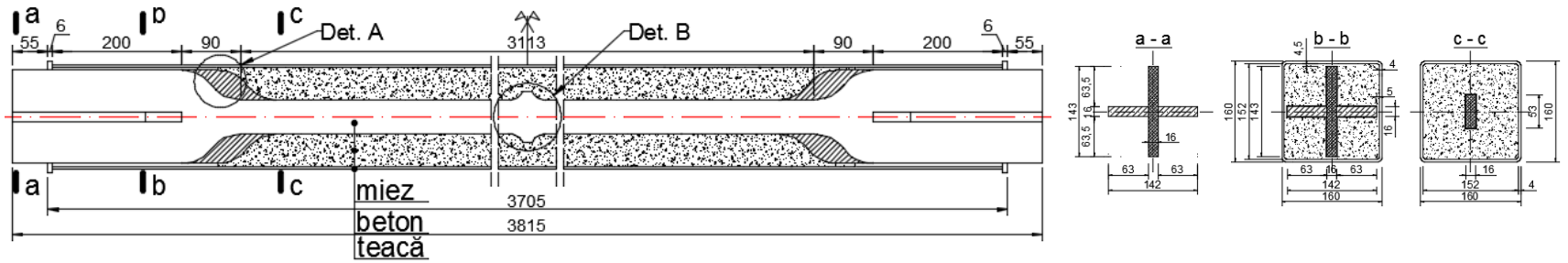
- **Soluția tehnică pentru zona de îmbinare (cu bolț, cu șuruburi, cu sudură)**

- **Realizarea mecanismului de împiedicare a flambajului (țeavă umplută cu beton, subansamblu metalic sudat/cu șuruburi)**

Concepte inițiale. BRB „convențional”

Propuneri pe baza studiului bibliografic:

- A



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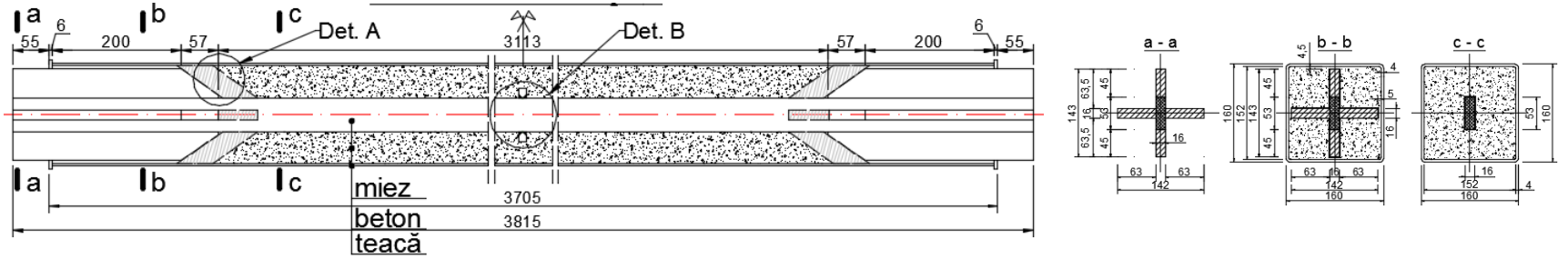
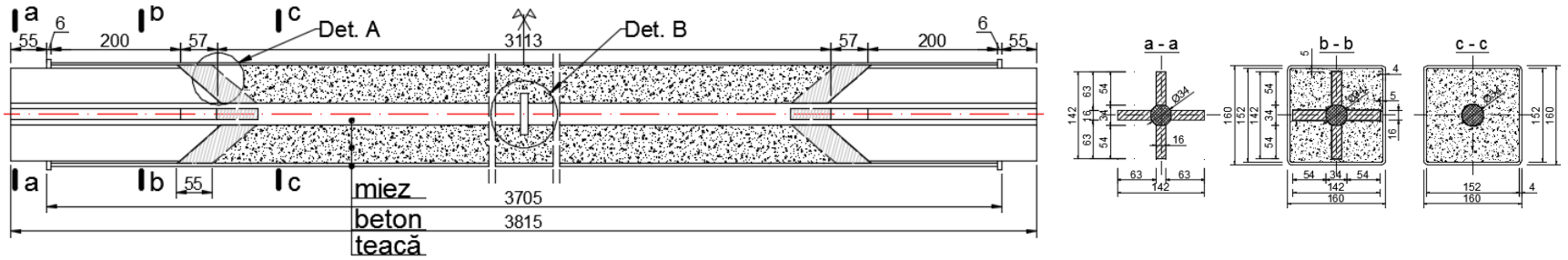


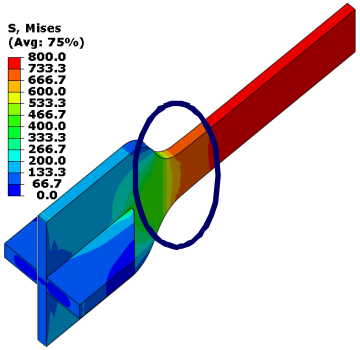
- C

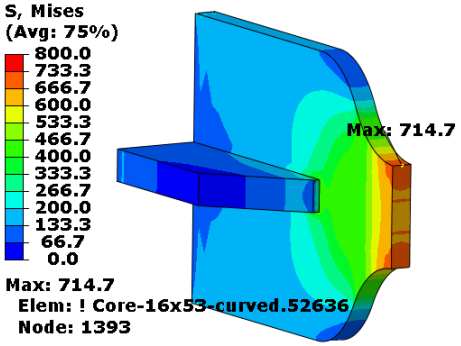


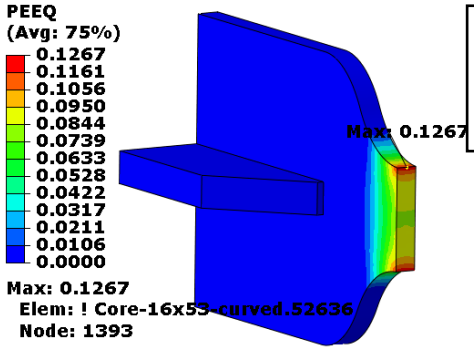
Pretestări numerice. Zona de tranziție

Evaluarea performanței/concepte propuse:

- A

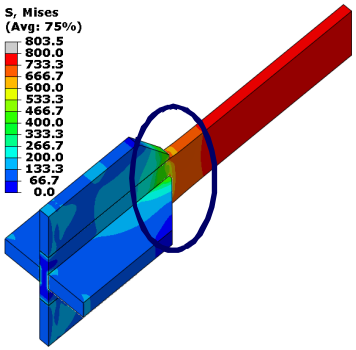


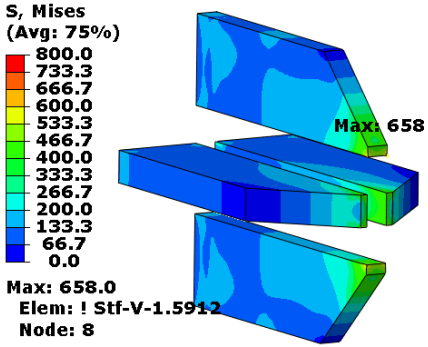


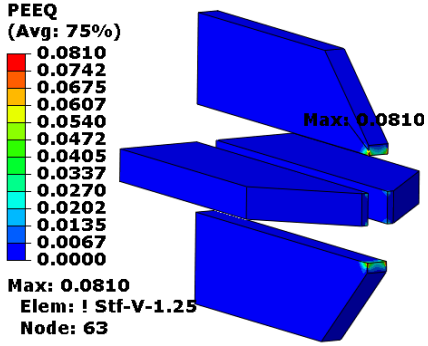


σ_{max} = 715 MPa
$PEEQ_{max}$ = 12.67 %
Fără concentratori

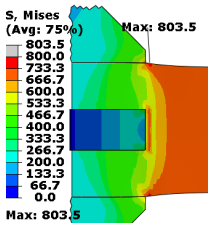
- B



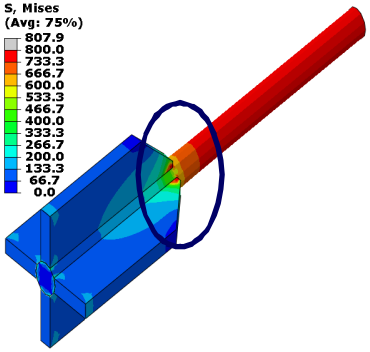


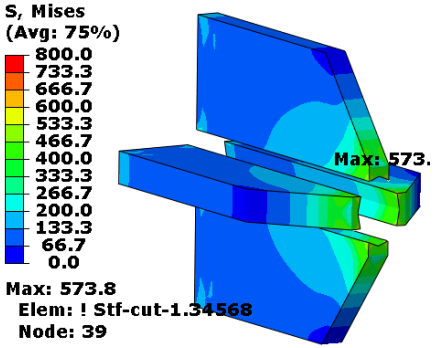


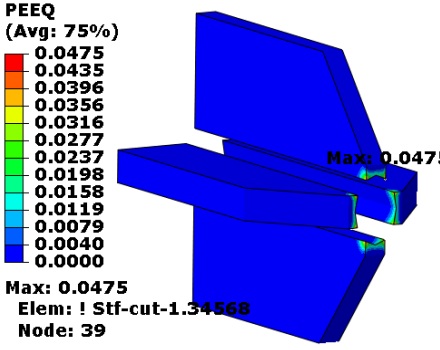
σ_{max} = 658 MPa
$PEEQ_{max}$ = 8,10 %



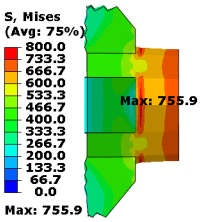
- C







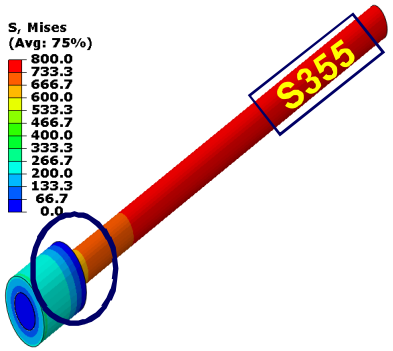
σ_{max} = 574 MPa
$PEEQ_{max}$ = 4,75%

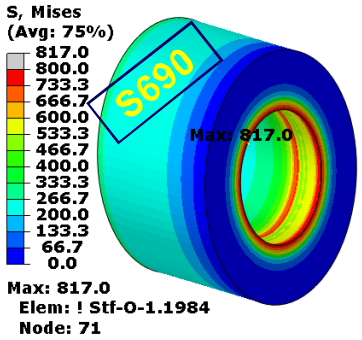


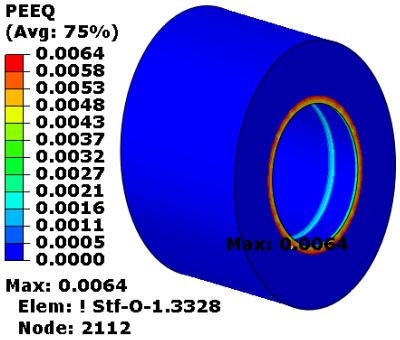
Pretestări numerice. Zona de tranziție

Evaluarea performanței/alte concepte:

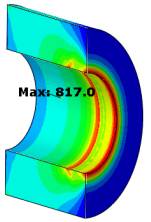
- D



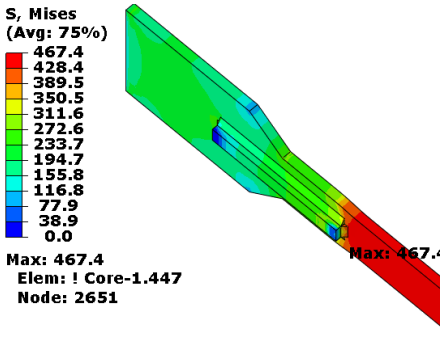


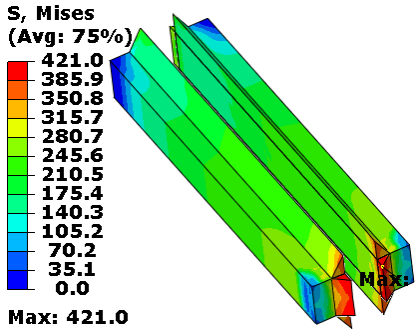


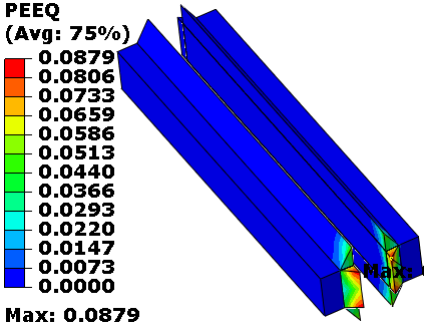
σ_{max} = 817MPa
$PEEQ_{max}$ = 0,64%



- E

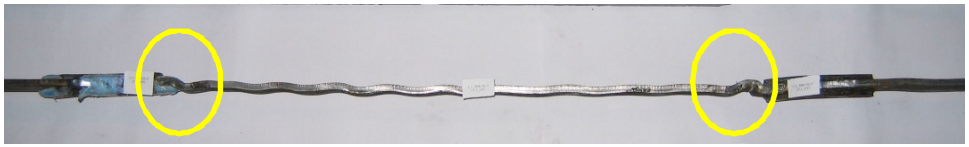






σ_{max} = 421 MPa
$PEEQ_{max}$ = 8,79 %

Bordea, 2007



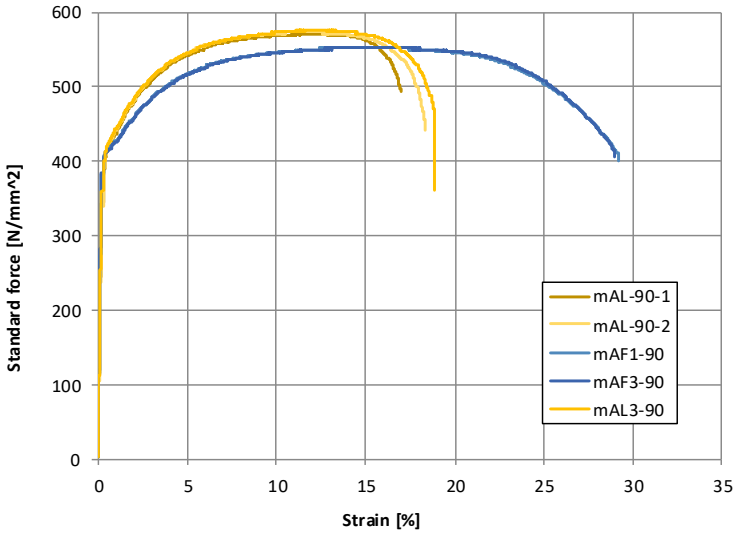
Pretestări numerice. Zona de tranziție

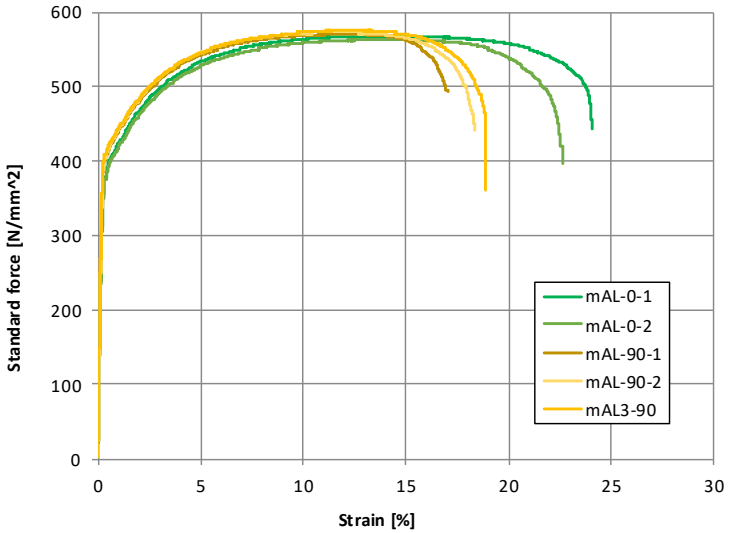
- **Centralizator. Performanța:**

Soluția BRB	Descrierea soluției	σ_M [MPa]	PEEQ [%]	Observații
tip A	racord prin prelucrare mecanică + 2 rigidizări (S355) (R=56 mm)	715	12,67	➢ σ & PEEQ mari ➢ Lipsa concetratorilor de σ (reducere graduală) ➢ Performanță adecvată
tip E	racord prin prelucrare mecanică (cu defect) + 2 rigidizări (S235) (21°)	421	8,79	➢ σ & PEEQ mari ➢ Fisuri incipiente ➢ În general, ruperea nu s-a produs în zona zudată.
tip B1	miez 16x53 secț. const. + 4 rigidizări S355 (35°)	658	8,10	➢ σ & PEEQ moderate ➢ Concentratori de σ + plasticizarea rigidizărilor
tip B2	miez 16x53 secț. const. + 4 rigidizări S690 (35° & 45°)	818	5,73	➢ σ & PEEQ reduse ➢ Concentratori de σ + plasticizarea rigidizărilor
tip C1	miez ∅ 34 secț. const. + 4 rigidizări S355 (41°)	574	4,75	➢ σ & PEEQ moderate ➢ Concentratori de σ + plasticizarea rigidizărilor
tip C2	miez ∅ 34 secț. const. + 4 rigidizări S690 (41°)	808	2,41	➢ σ & PEEQ reduse ➢ Concentratori de σ + plasticizarea rigidizărilor
tip D	miez ∅ 34 secț. const. + 1 rigidizare (bucșă) S690	817	0.64	➢ σ & PEEQ reduse ➢ Concentratori de σ + plasticizarea rigidizărilor

Pretestări experimentale. Zona de tranziție

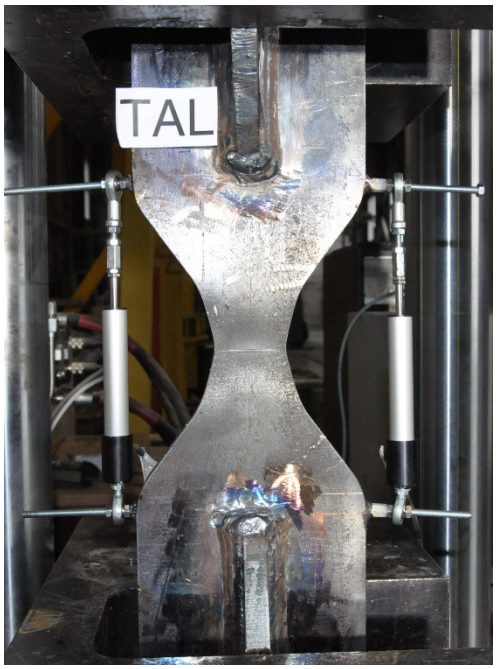
- **Evaluarea influenței tehnologiei de debitare:**

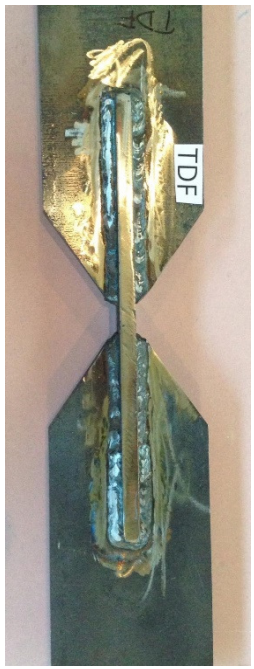


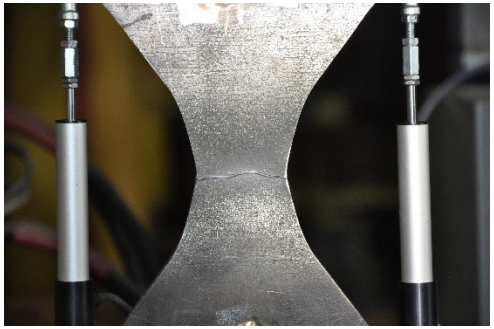


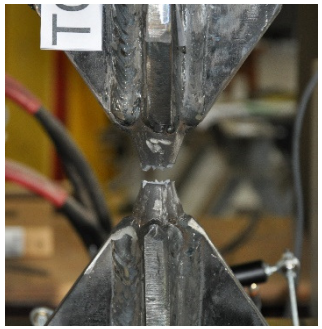
Pretestări experimentale. Zona de tranziție

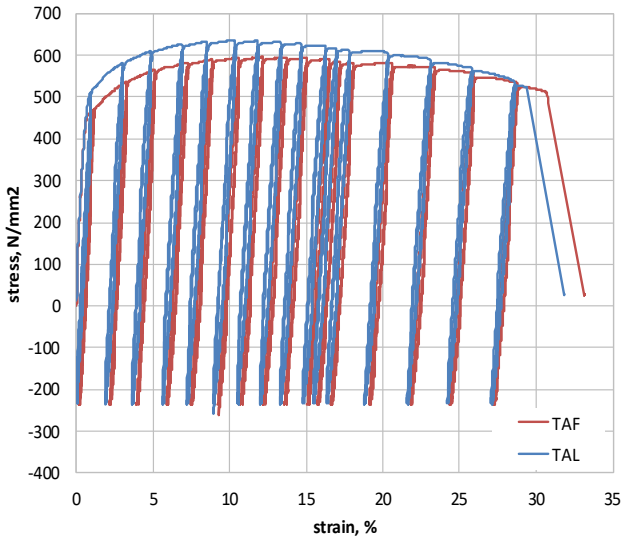
- **Evaluarea influenței detaliului constructiv:**

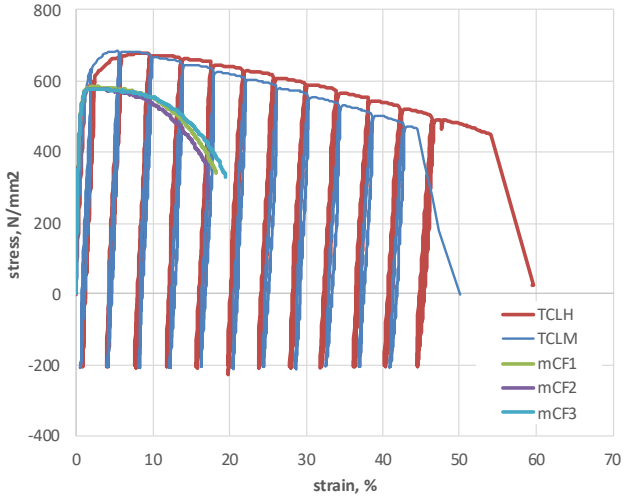












Dezvoltarea modelelor MEF ale BRB-urilor

Modelare MEF. Calibrarea modelului

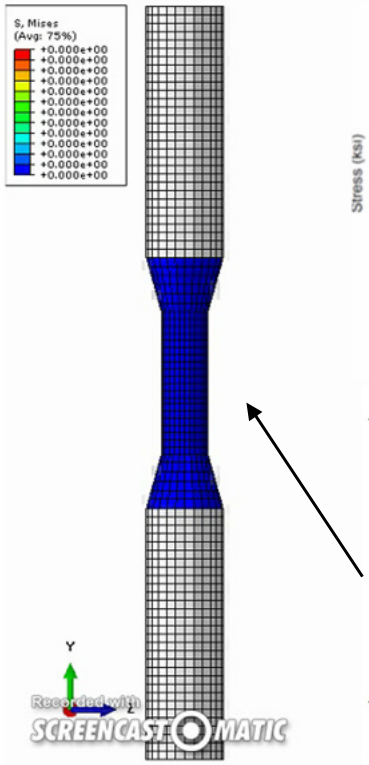
Nivelul componentelor:

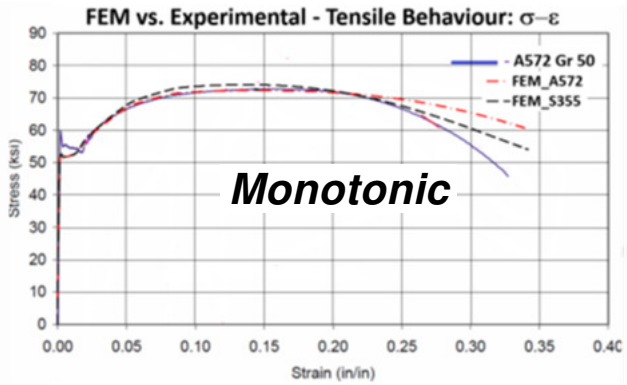
- **Modele de material:**
  - **Oțel:** consolidare combinată (NLKIN + MISO)
  - **Beton**: CDP, elastic isotropic (C25/30,)
- **Interacțiuni:** legi de contact (coeficient de frecare, f)
- **Dimensiunea spațiilor (1 mm). Tip de EF (C3D8I)**

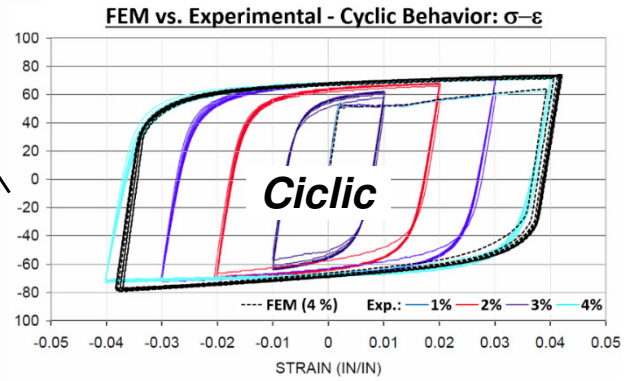
(calibrare pe baza Kaufmann et al. (2001))

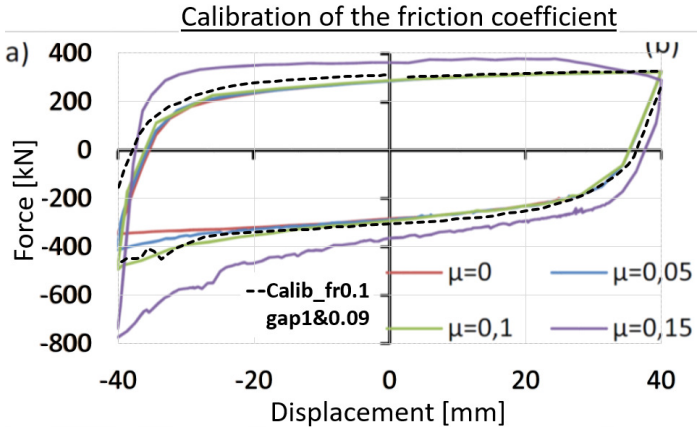
(calibrare pe baza EC2)

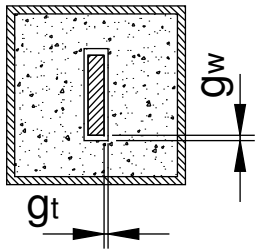
(calibrare pe baza Budahazy (n.d.))

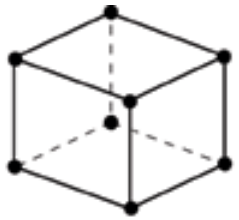








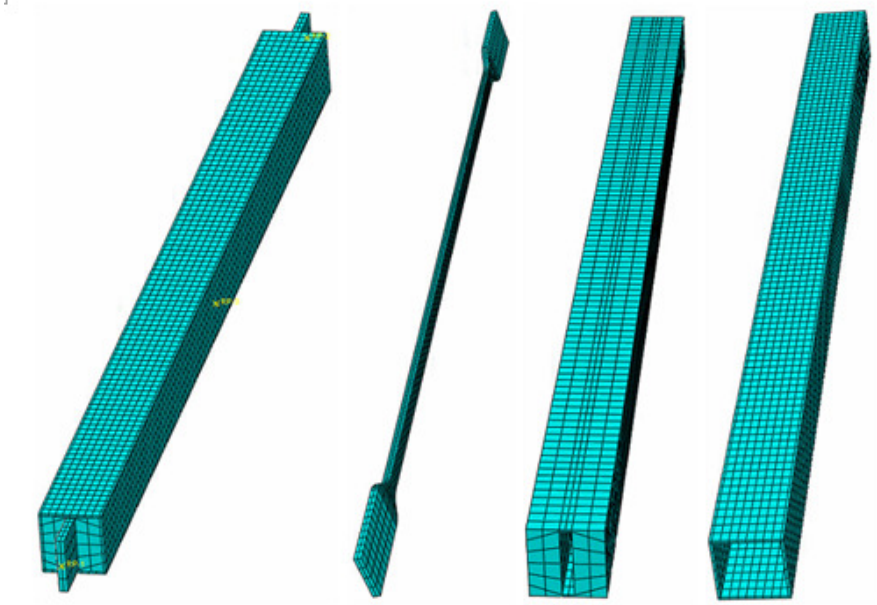


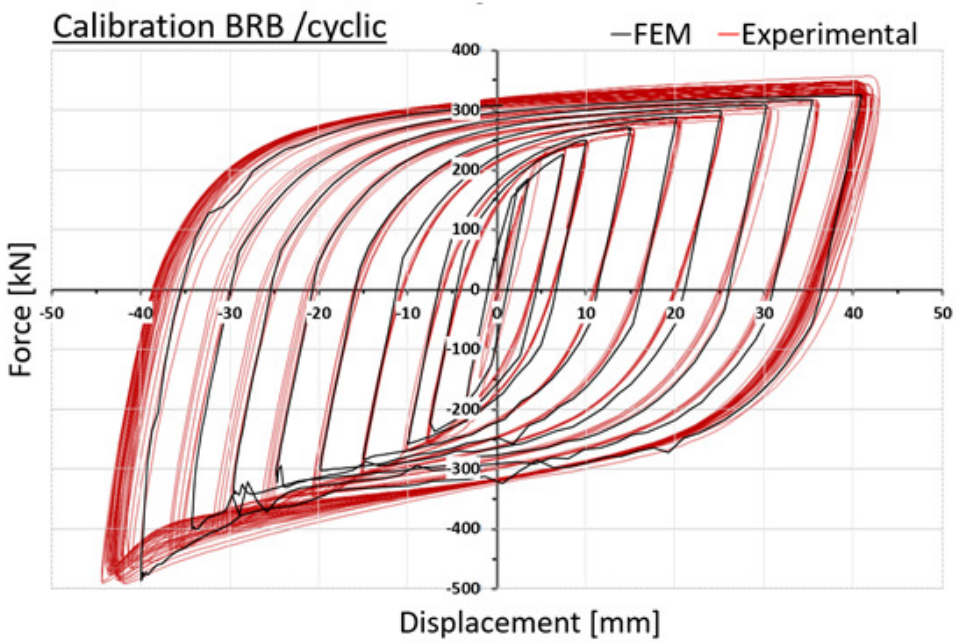


Modelare MEF. Calibrarea modelului

Nivelul BRB (ciclic)

(calibrare pe baza Dunai et al. (2011))





Dezvoltarea soluțiilor BRB „convenționale” folosind simulări numerice

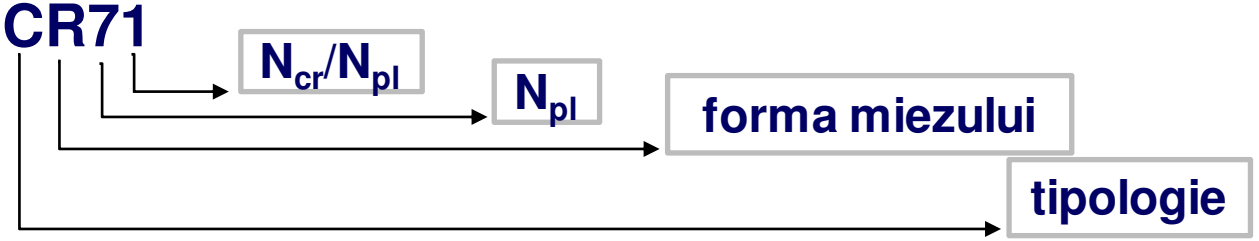
Program de dezvoltare

- **Capacități nominale:**
  - $N_{pl,3}$ = 300 kN;
  - $N_{pl,7}$ = 700 kN.

- **Forma secțiunii transversale a miezului:**
  - Dreptunghiulară (R): 14 x 60 mm și 20 x 99 mm, S355;
  - Pătrată (S): 30 x 30 mm și 45 x 45 mm, S355;
    (pentru a evalua influența formei miezului).

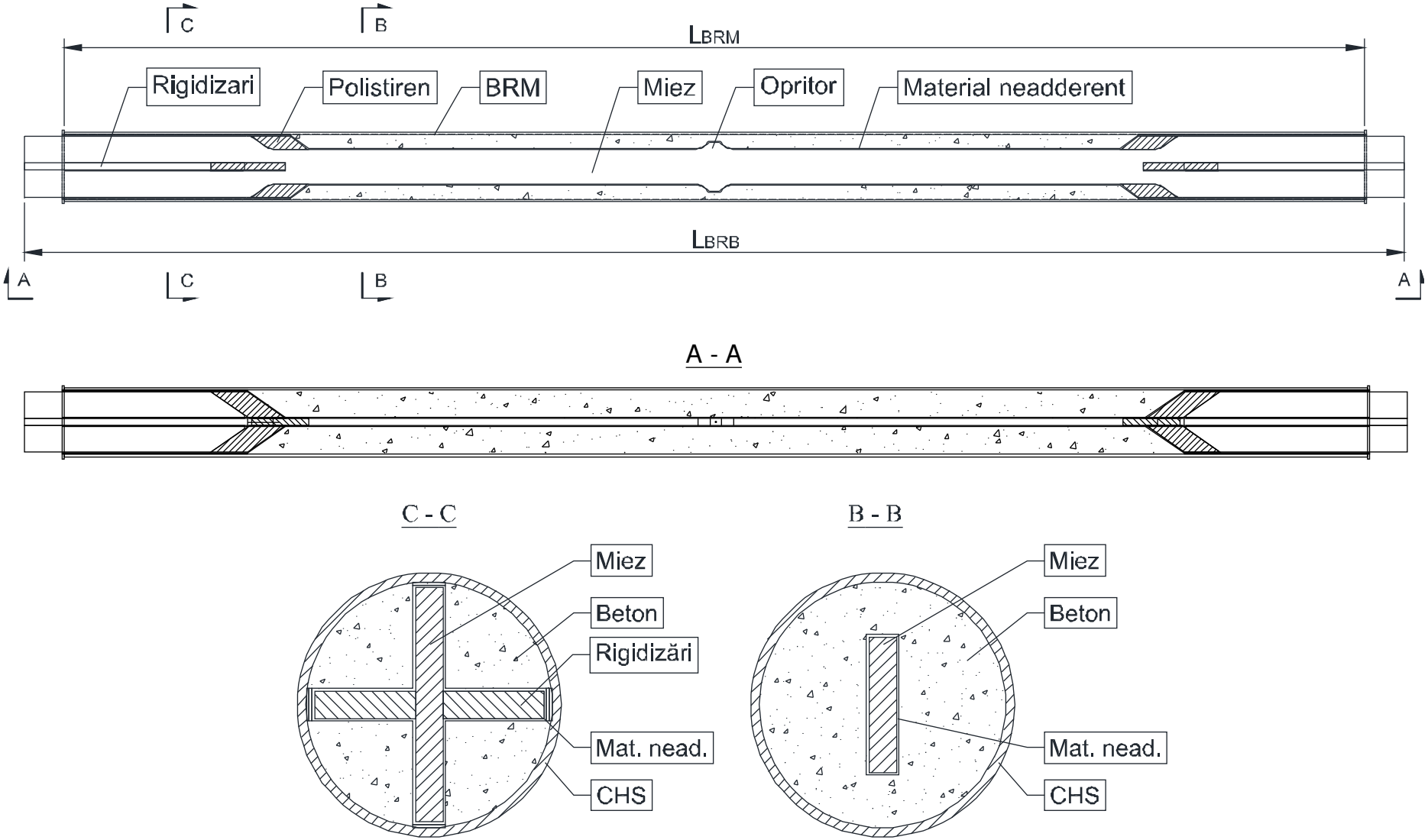
- **BRM:**
  - N_{cr}/N_{pl} = 1,5 (1);
  - N_{cr}/N_{pl} = 3,0 (3);
    (pentru a evalua metodologia de proiectare propusă de literatură).

BRB ID: CR71



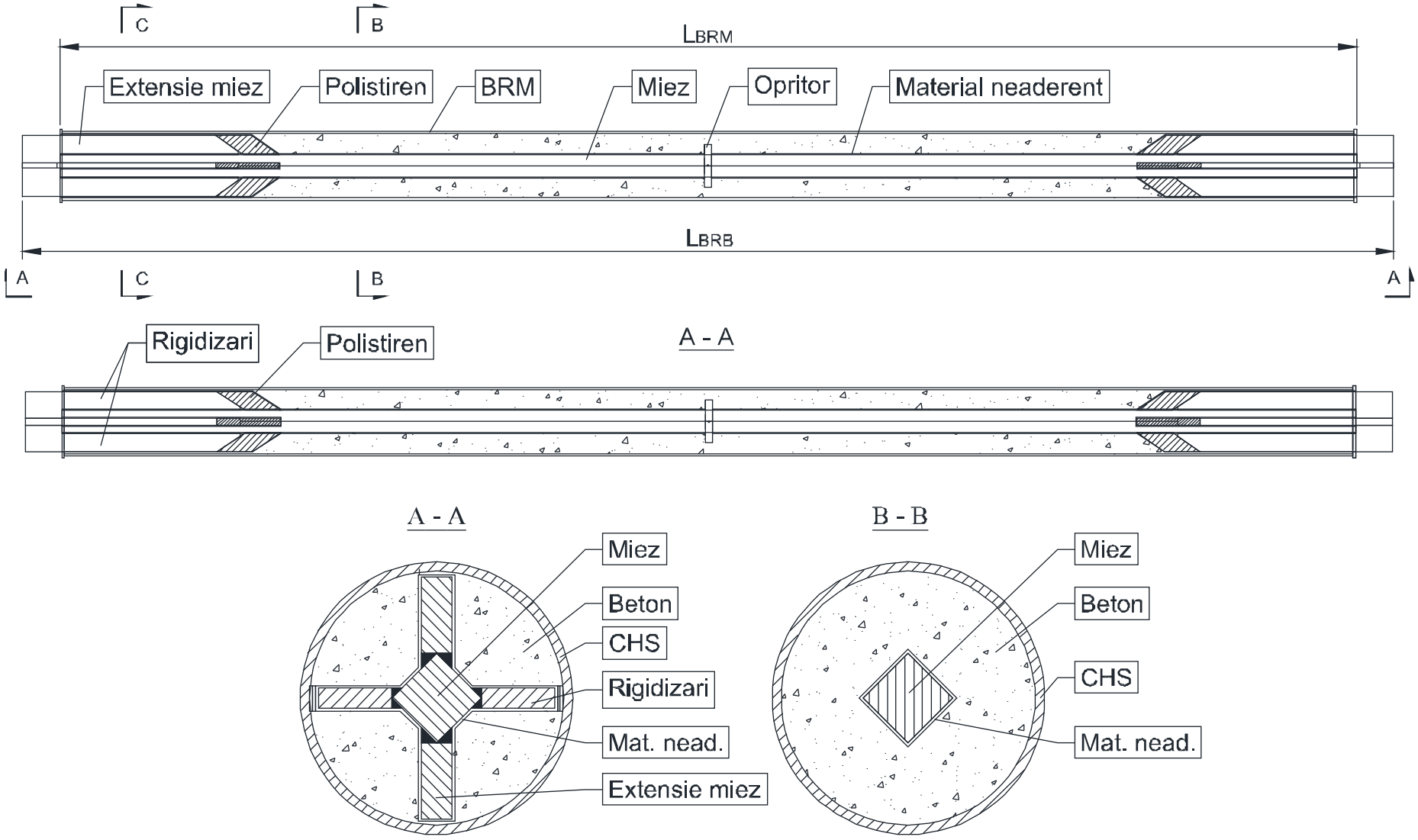
Concepte BRB selectate

Concept 1 (300 & 700 kN): miez dreptunghiular + rază racord



Concepte BRB selectate

Concept 2 (300 & 700 kN): miez pătrat + 4 rigidizări sudate



Evaluarea performanței ciclice

Criterii de comparație:

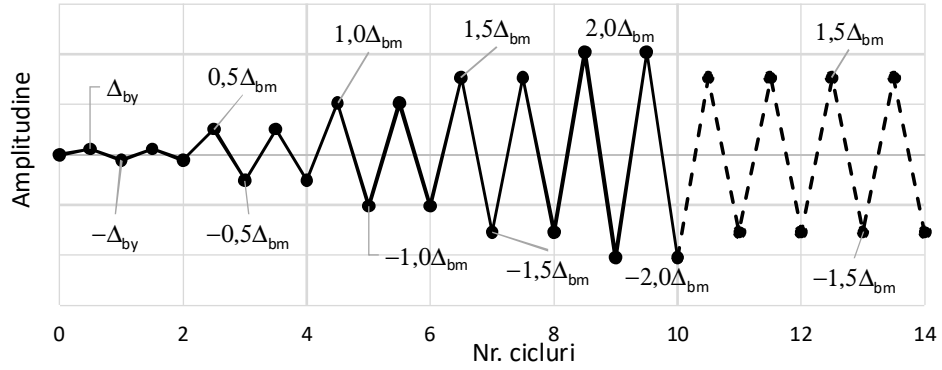
- Factorul de ajustare la compresiune (β);

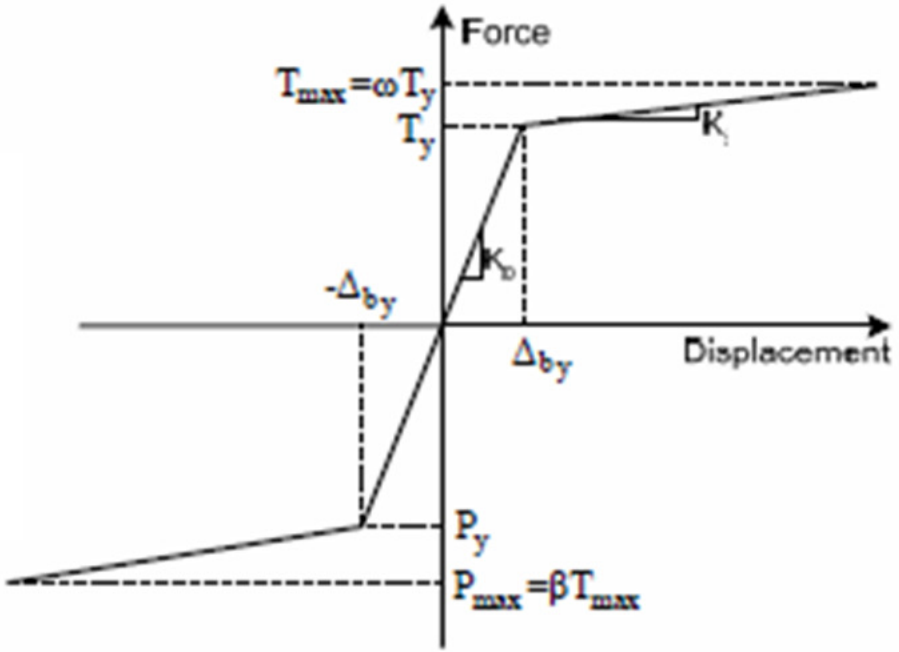
  1.0 <= β <= 1.3

- performanța globală;
- deformația ultimă (capacitatea de ductilitate)
- satisfacerea protocolului de încărcare ANSI/AISC 341-16.

$$\omega = T_{\max} / A \cdot f_{y,m}$$

$$\beta = P_{\max} / T_{\max}$$



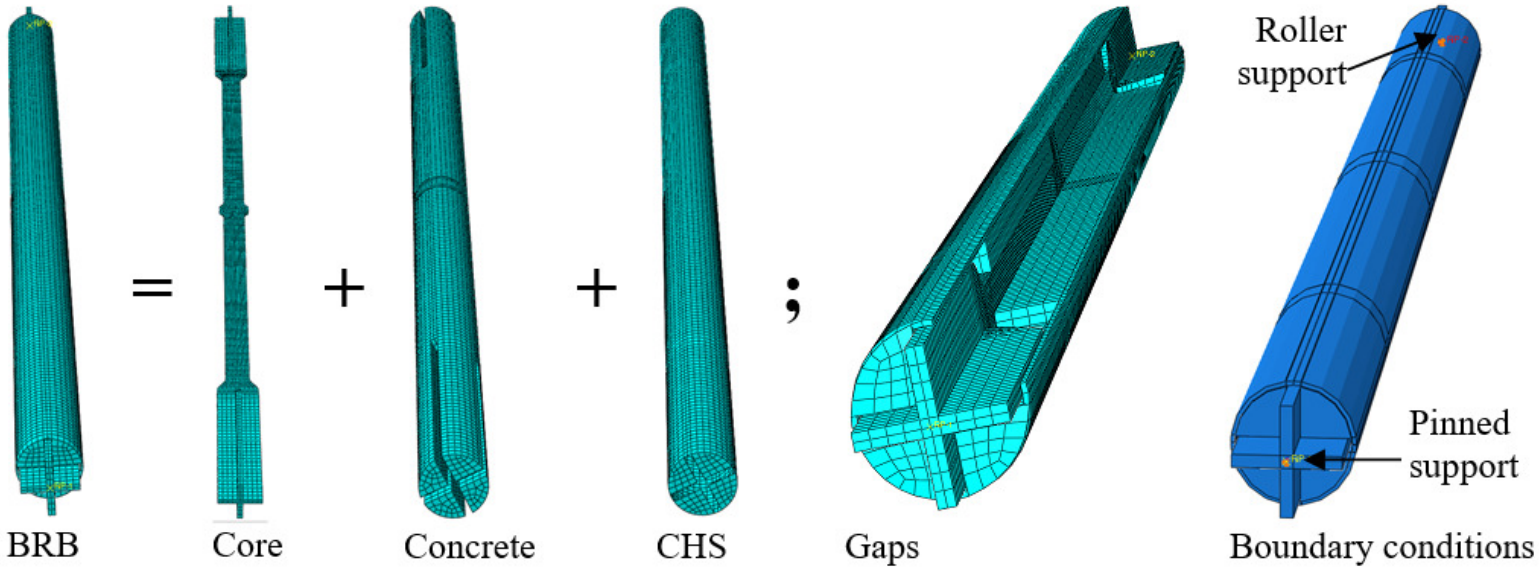


Modelarea soluțiilor BRB

- **Modele de material: NLKIN+MISO/componentele din oțel; CDP sau elastic/componentele din beton.**
- **Tip de EF/component: C3D8I/miez, S4R/țeavă, C3D8R/beton.**
- **Material neaderent = spațiu + f0,1.**
- **Contact general: normal = "Hard"; tangențial = "Penalty" (f0,1; f0,4)**
- **Imperfecțiuni, $L_{BRM}/1000$ = 3,7 mm.**
- **Solver utilizat: Static General, Dynamic Implicit (cvasi-static) și Dynamic Explicit (validat prin compararea energiilor).**

(între miez și beton)

(între beton și țeavă)

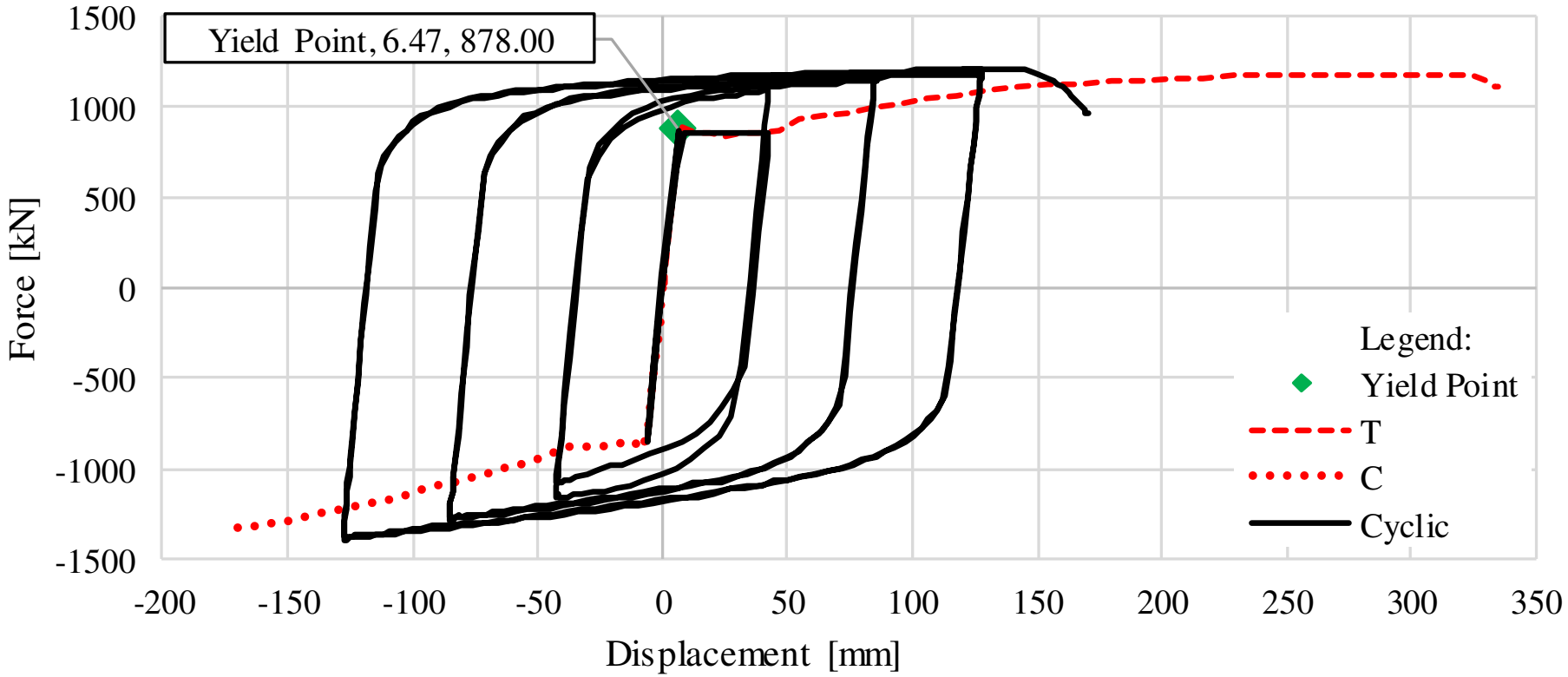


Programul numeric

Studiu parametric pentru soluția BRB 700 kN „convențional”			
Model ID	Parametru	Parametru analizat	
		ID	Valoare
CR73-g1-f.1	g1	1. Spațiu	1,1,1,1
CR73-g12-f.1	g1/2		1,2,2,1
CR73-g2-f.1	g2		2,2,2,2
CR71-g12-f.1	1	2. BRM	$P_e/P_y = 1.5$
CR73-g12-f.1	3		$P_e/P_y = 3.0$
CR73-g12-f.1	R	3. Forma secțiunii	dreptunghiular
CS73-g1-f.1	S		pătrat
CR73-g12-f.05	f.05	4. Frecare	0.05
CR73-g12-f.1	f.1		0.1
CR73-g12-f.15	f.15		0.15
CR73-g12-f.2	f.2		0.2

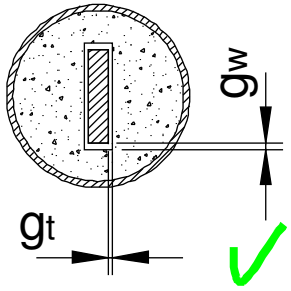
Influența tipului de încărcare

- **CR73-g12-f.1 = model de referință**
- **Rezistența plastică, N_p = 878 kN (unde, f_y = 355 x γ_{ov})**
- **Forța maximă de tracțiune: $T_{max,cic}$ / $T_{max,m}$ = 1,02 >> 2,2%**
- **Intervalul de deformație: $\Delta_{d,m}$ / $\Delta_{d,cyc}$ = 1,14 >> 13,7 %**

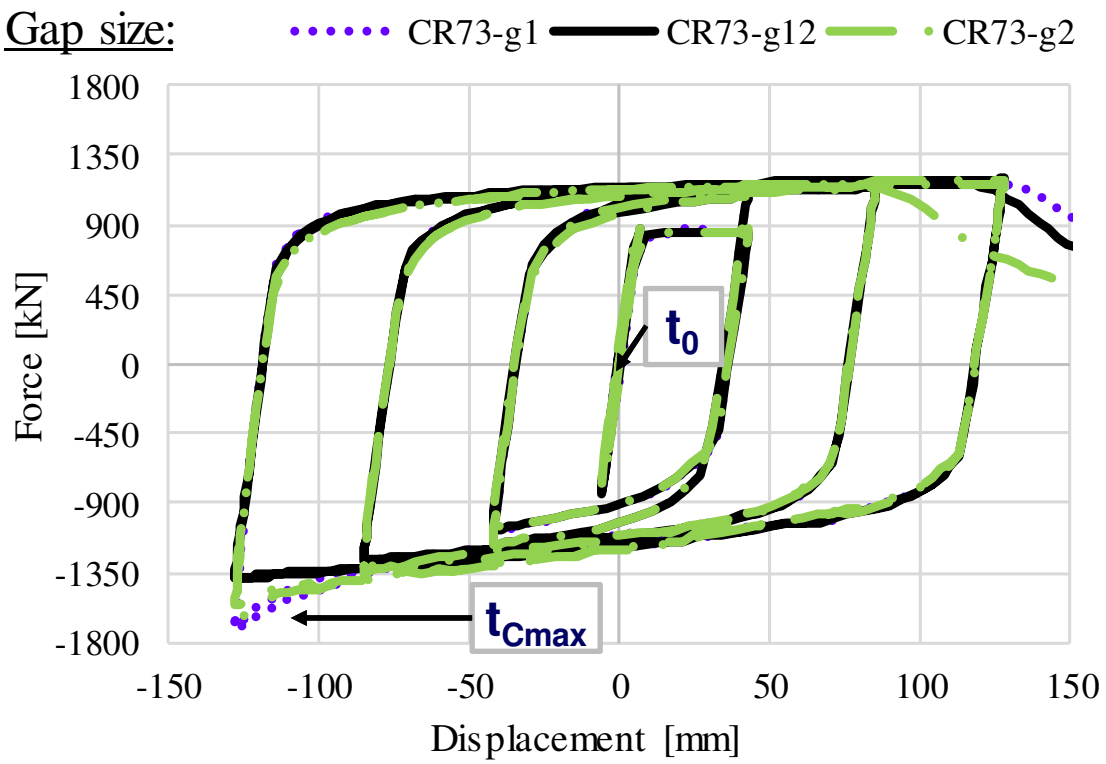


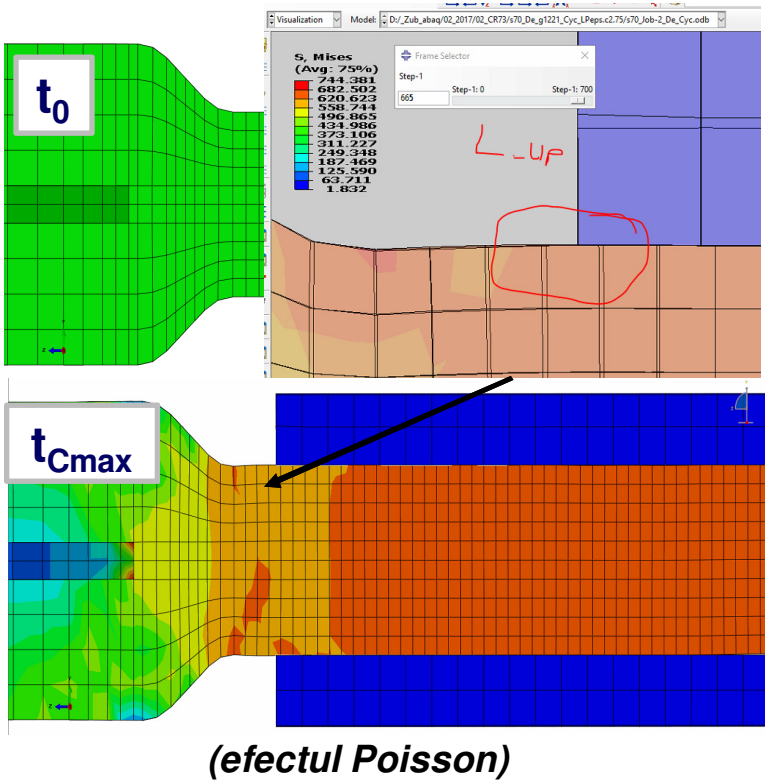
Influența dimensiunii spațiilor dintre miez și BRM

- Pe direcția grosimii (g_t);
- Pe direcția lățimii (g_w).



g_t [mm]	& g_w [mm]	β
1	& 1	1.43
1	& 2	1.16
2	& 2	1.38

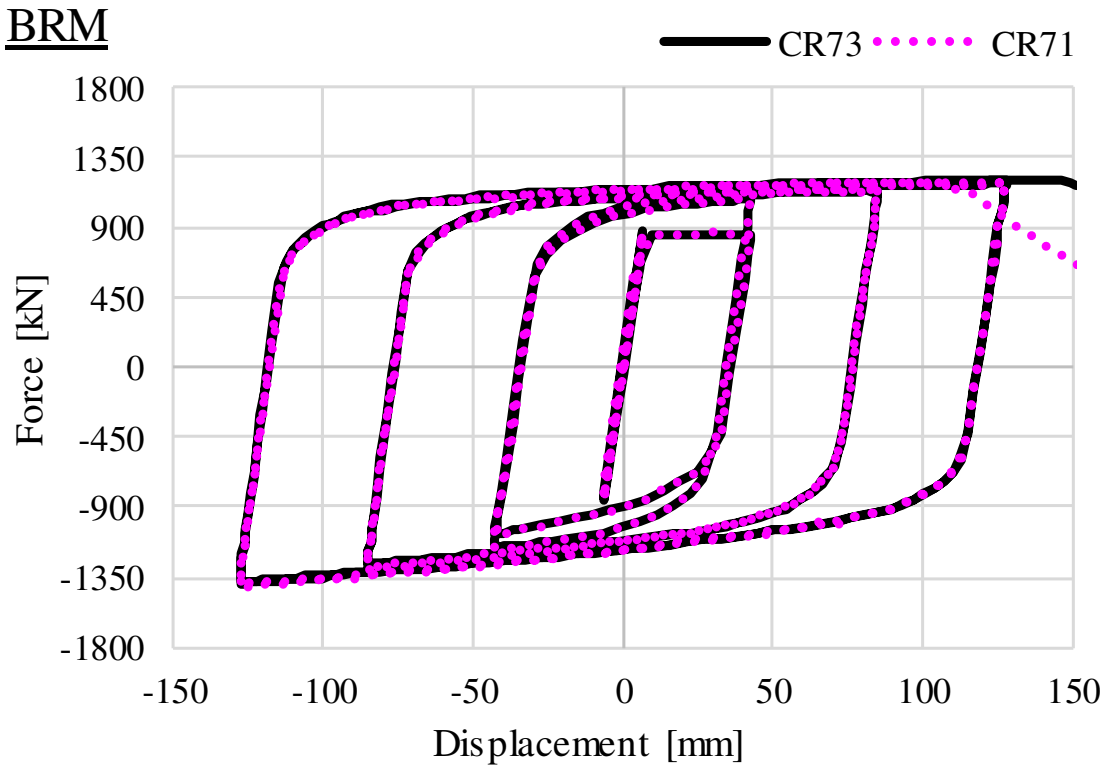


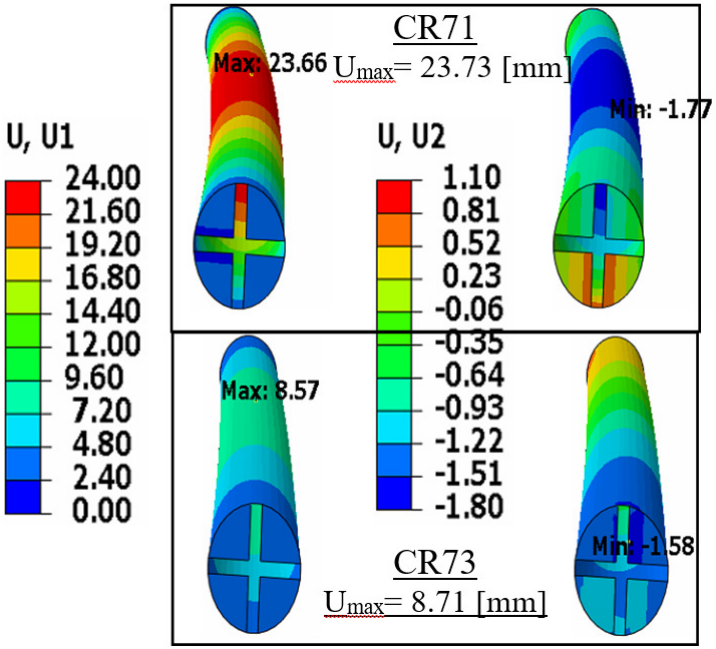


(efectul Poisson)

Influența forței critice de flambaj a BRM

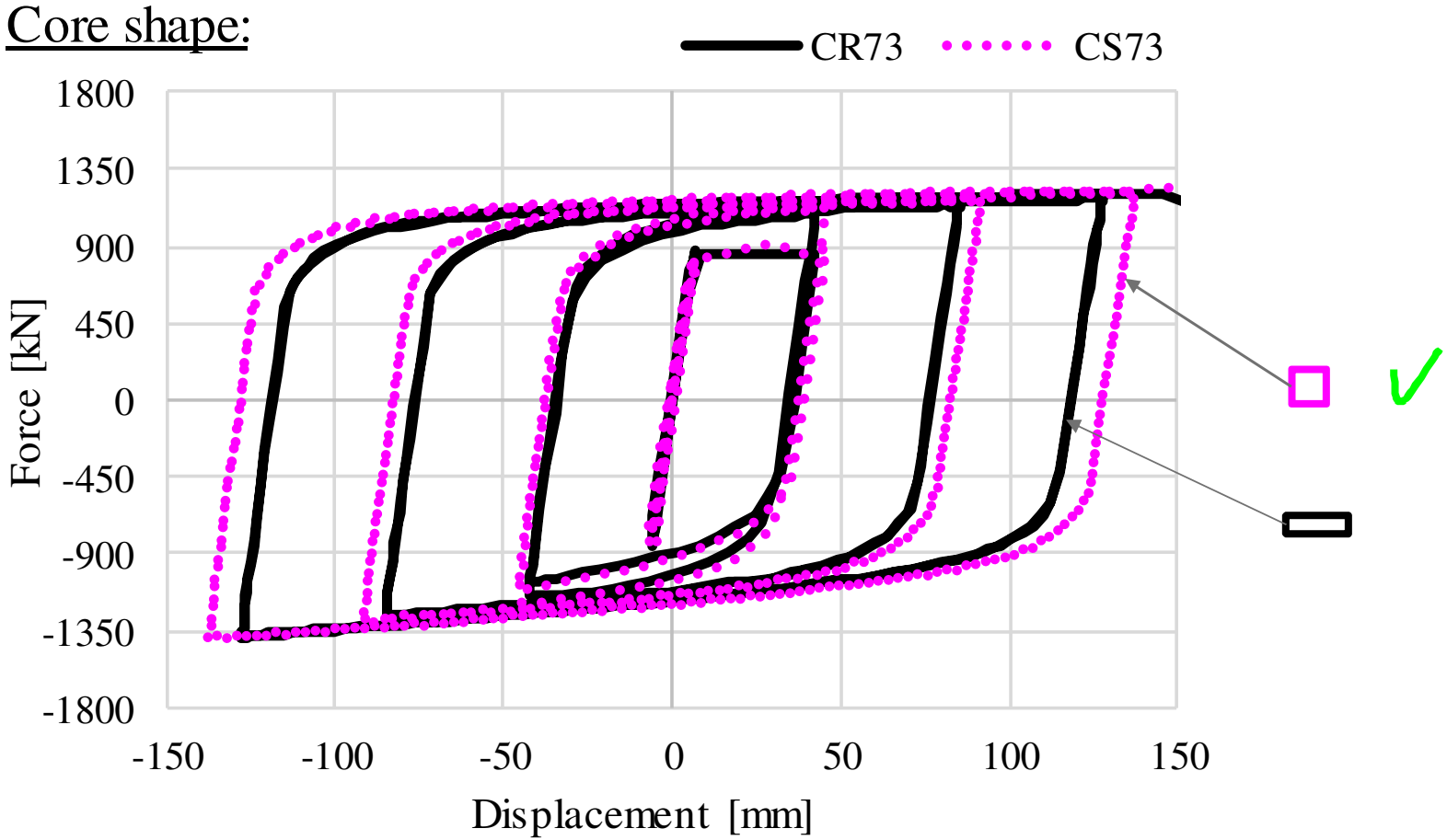
- N_{cr}/N_{pl} = 1.5 (1): β_1 = 1.19; U_{CR71} = 23.73 mm;
- N_{cr}/N_{pl} = 3.0 (3): β_3 = 1.16; U_{CR71} = 8.71 mm. ✓





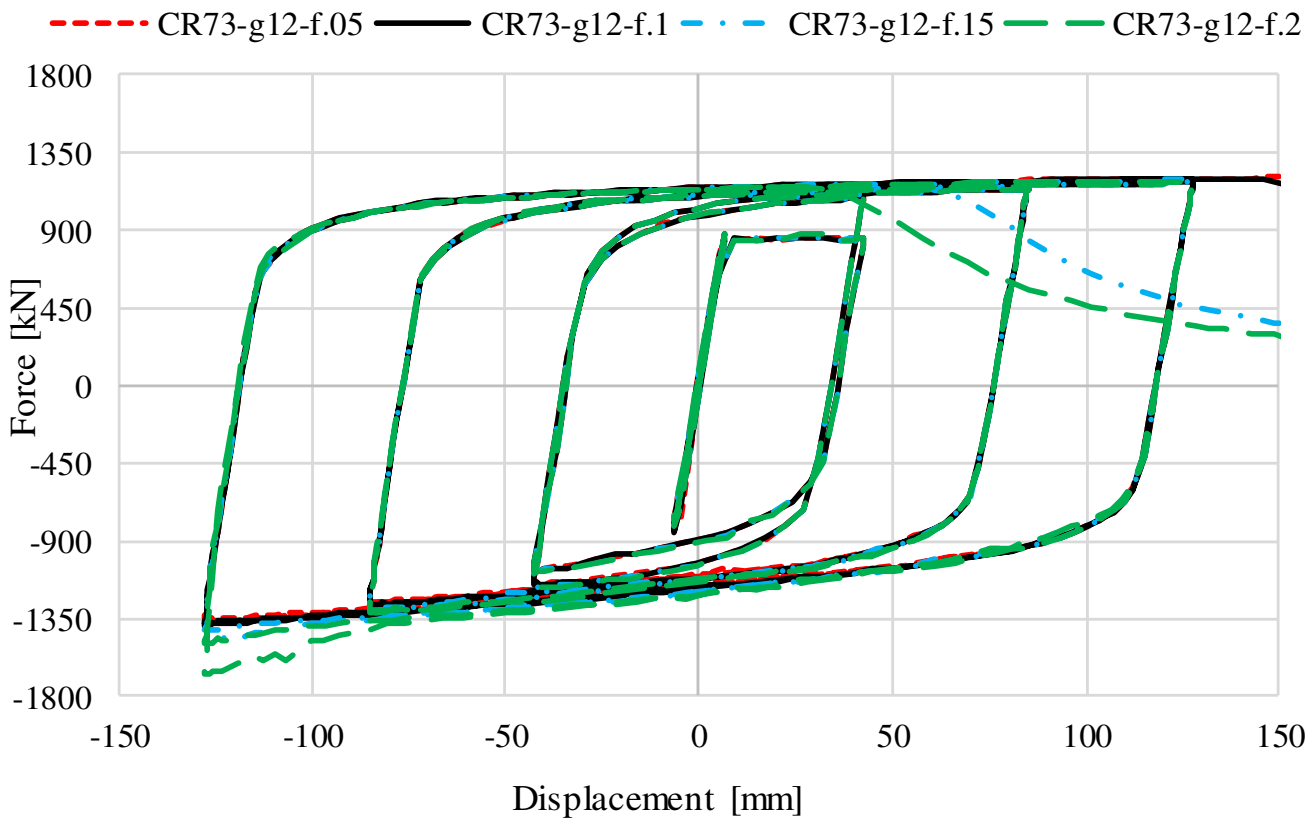
Influența formei miezului

- **Pătrat (S): β = 1.13; ductilitate mai mare;**
- **Dreptunghiular (R): β = 1.16; ductilitate mai mică.**



Influența valorii coeficientului de frecare

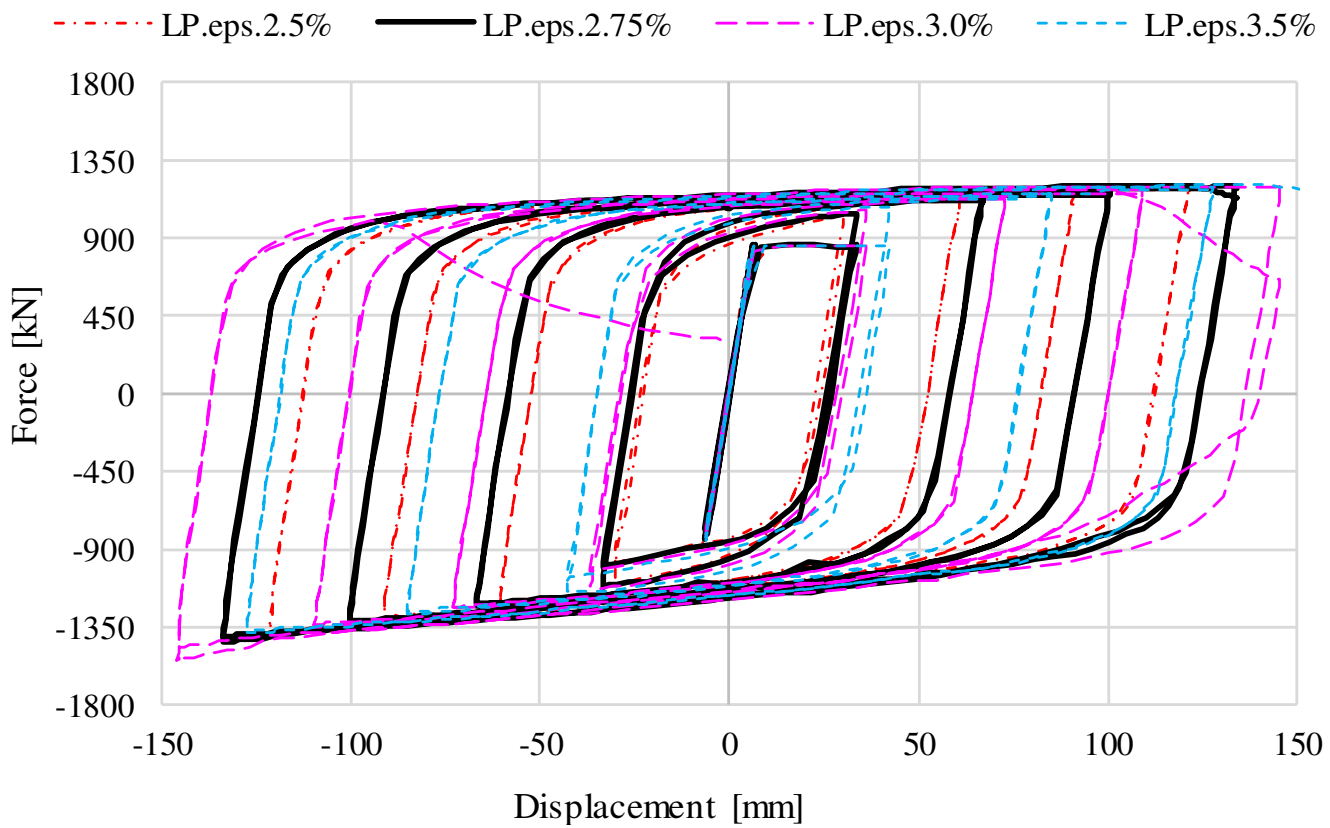
- **CR73-g12-…** **f.05** **f.1** **f.15** **f.2**
- **β** **1.13** **1.16** **1.24** **1.41**
- **Ductilitatea** **mare** ⟶ **mică**



Influența nivelului deformației specifice din miez

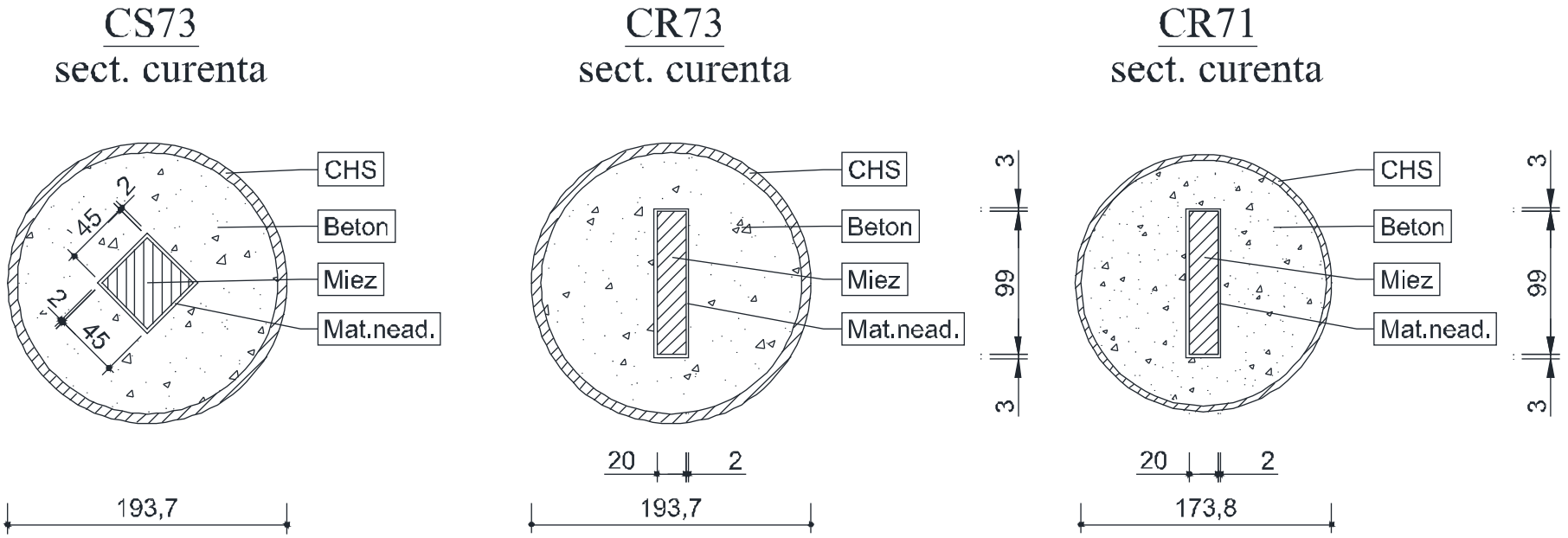
LP = funcție de 2xε_{core}

CR73-g12-f.1	CID	CID/Δ_{by}	Status
ε 2.5%	2224	344	complet
ε 2.75%	2467	381	complet
ε 3.0%	2710	419	cedare
ε 3.5%	3196	494	cedare



Pretestări numerice. BRB convențional

- **Forma secțiunii transversale a miezului: pătrată.**
- **BRM: P_{cr}/P_{pl} = 3,0.**
- **Spațiu fizic, g_t&g_w: 2&2; 2&3**
- **Nivelul deformației specifice din miez: 5,5%**



Dezvoltarea soluțiilor BRB „uscate” folosind simulări numerice

Program de dezvoltare

- **O alternativă a BRB-urilor „convenționale":**
  - **Axare mai bună & control al spațiilor;**
  - **Fezabil producătorilor de confecții metalice.**

- **Capacități nominale:**
  - **$N_{pl,3}$ = 300 kN;**
  - **$N_{pl,7}$ = 700 kN.**

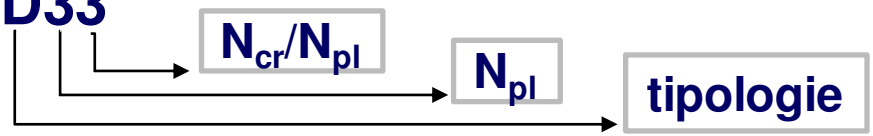
- **Forma miezului:**

  Dreptunghiular **(R): 14 x 60 mm și 20 x 99 mm, S355.**

- **BRM:**

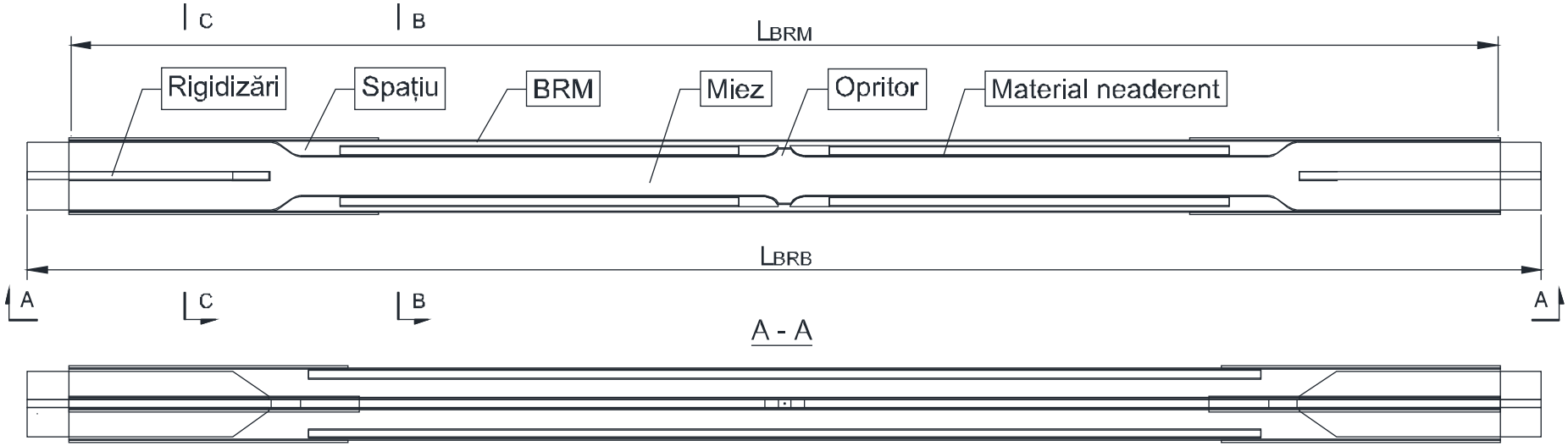
  4 SHS sudate, având N_{cr}/N_{pl} = 3.

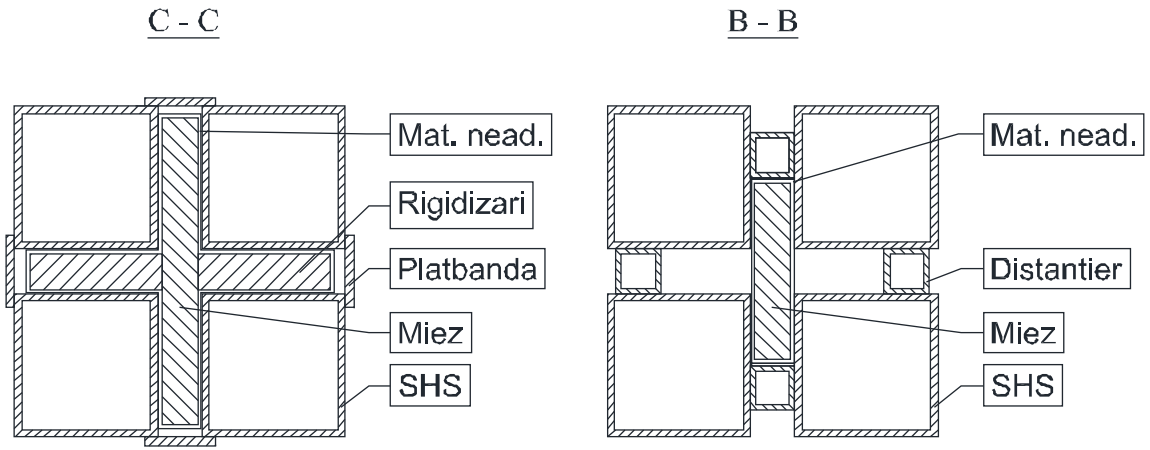
BRB ID: D33



Concept selectat

Concept 3 (300 & 700 kN): miez dreptunghiular + rază racord





Evaluarea performanței ciclice

Criterii de comparație:

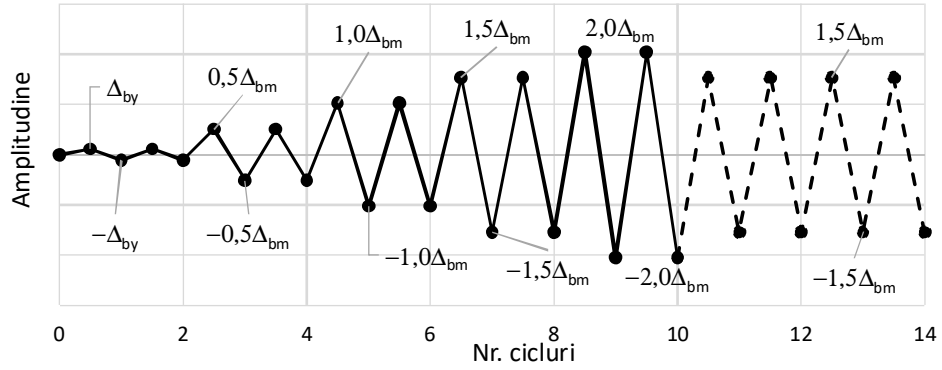
- Factorul de ajustare la compresiune (β);

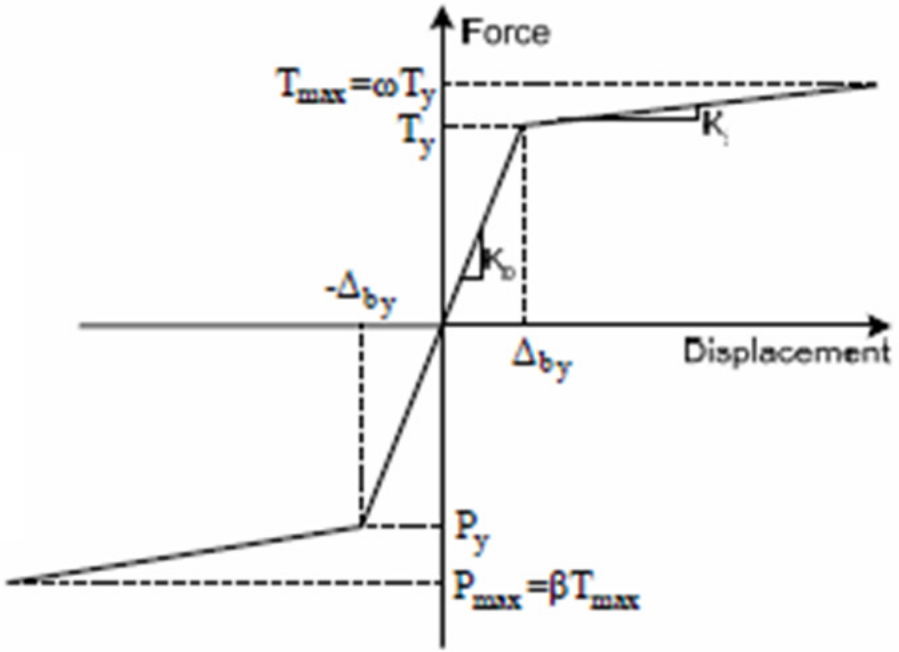
  1.0 <= β <= 1.3

- performanța globală;
- deformația ultimă (capacitatea de ductilitate)
- satisfacerea protocolului de încărcare ANSI/AISC 341-16.

$$\omega = T_{\max} / A \cdot f_{y,m}$$

$$\beta = P_{\max} / T_{\max}$$

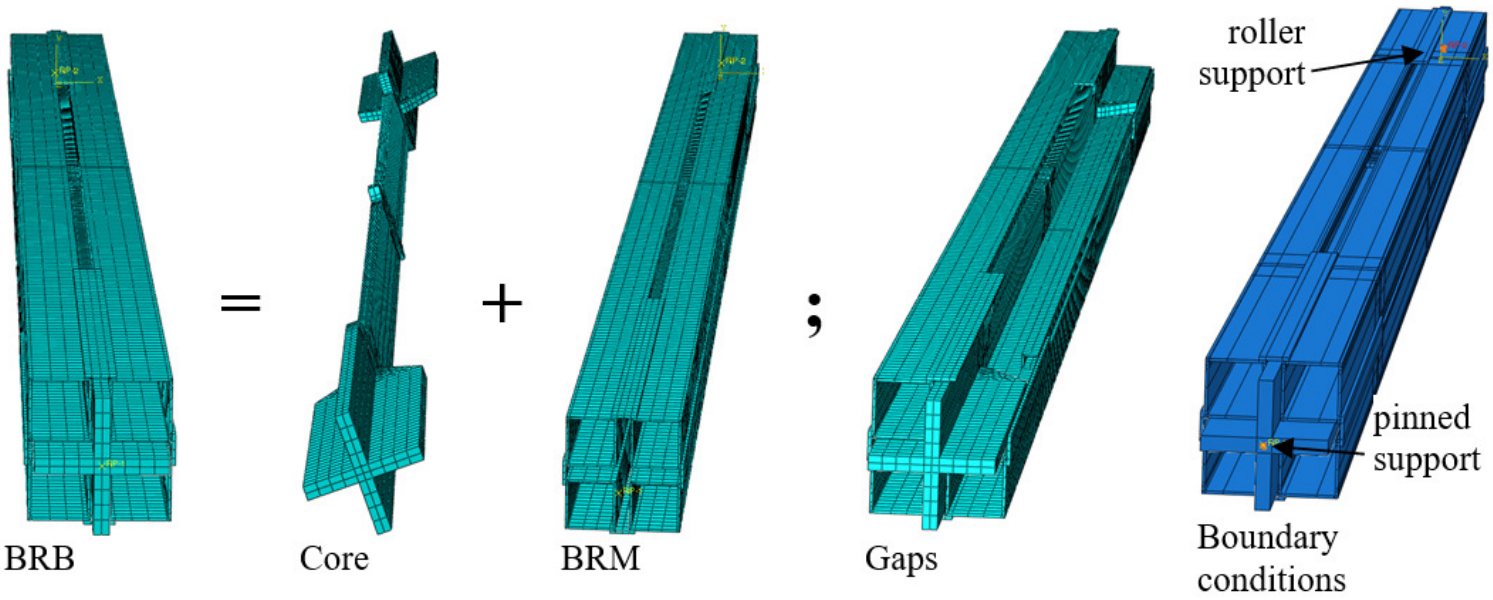




Modelarea soluțiilor BRB

- **Modele de material: NLKIN+MISO/componentele din oțel.**
- **Tip de EF/component : C3D8I/miez, S4R/țeavă.**
- **Material neaderent = spațiu + f0,1.**
- **Contact general: normal = "Hard"; tangențial = "Penalty" (f0,1).**
- **Imperfecțiuni, $L_{BRM}/1000$ = 3,7 mm.**
- **Solver utilizat : Dynamic Explicit.**

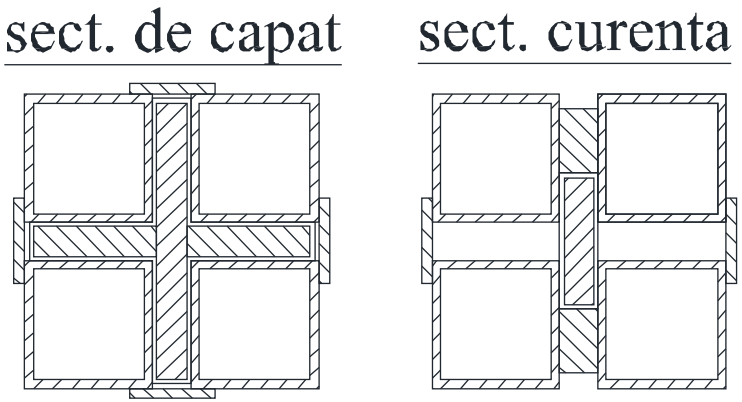
(între miez și țeavă)

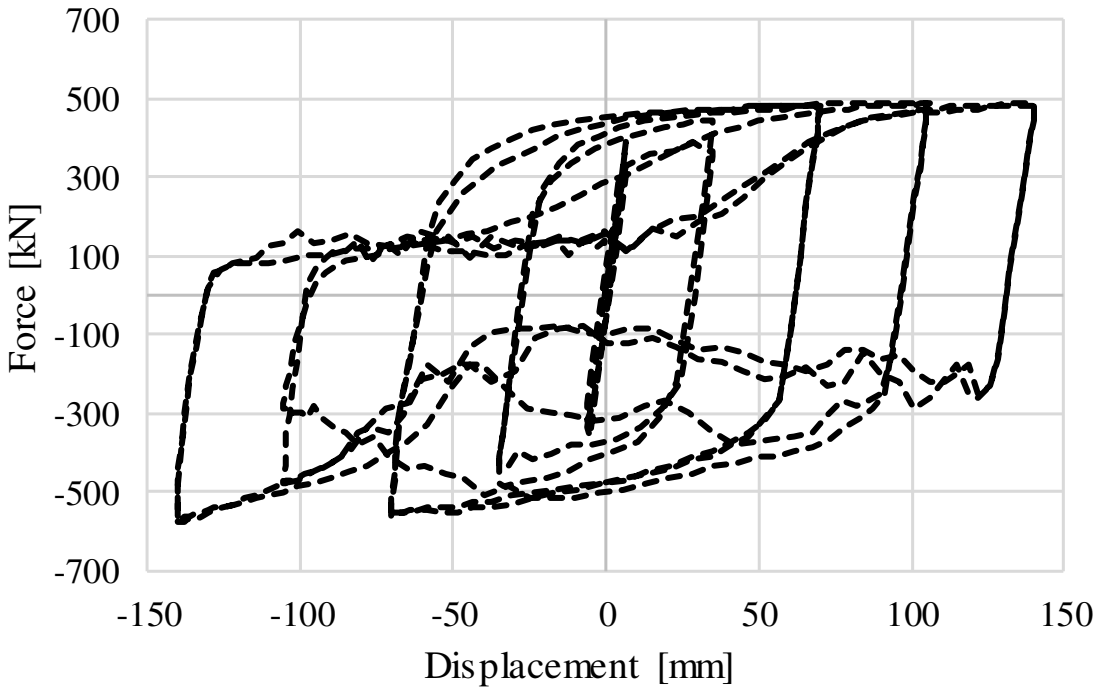


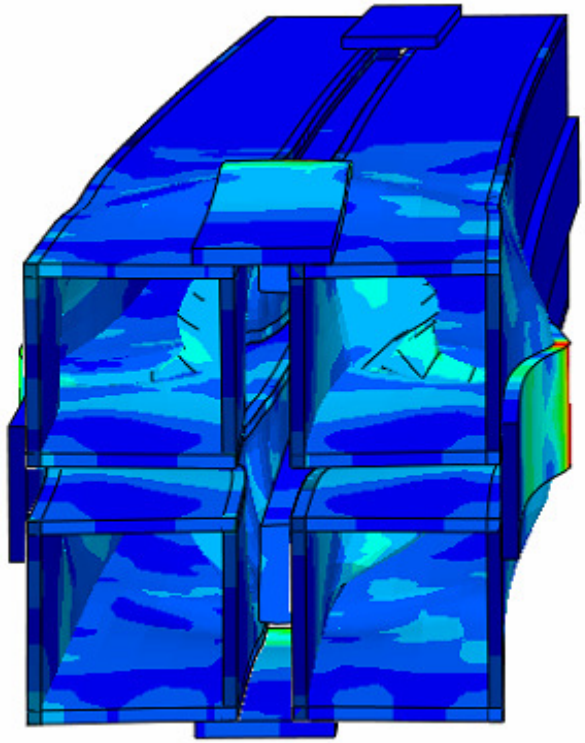
Dezvoltarea BRB-urilor „uscate" de 300 kN

Soluția inițială:

- **BRB: comportare ciclică slabă.**
- **BRM:**
  - **Voalarea locală a pereților SHS.**
  - **Comportare globală acceptabilă.**



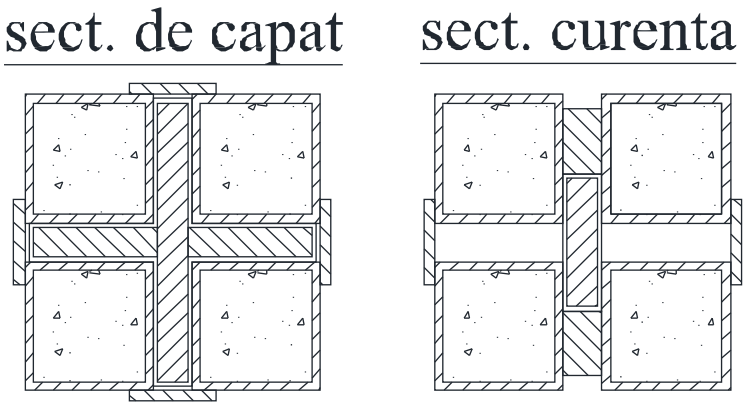


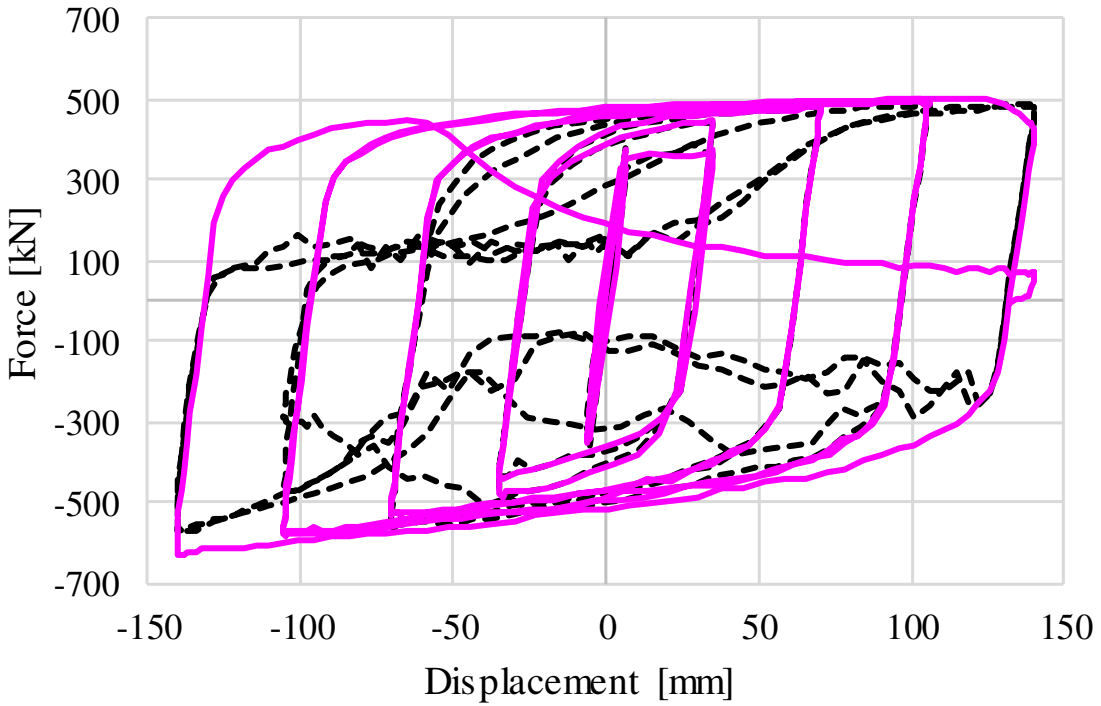


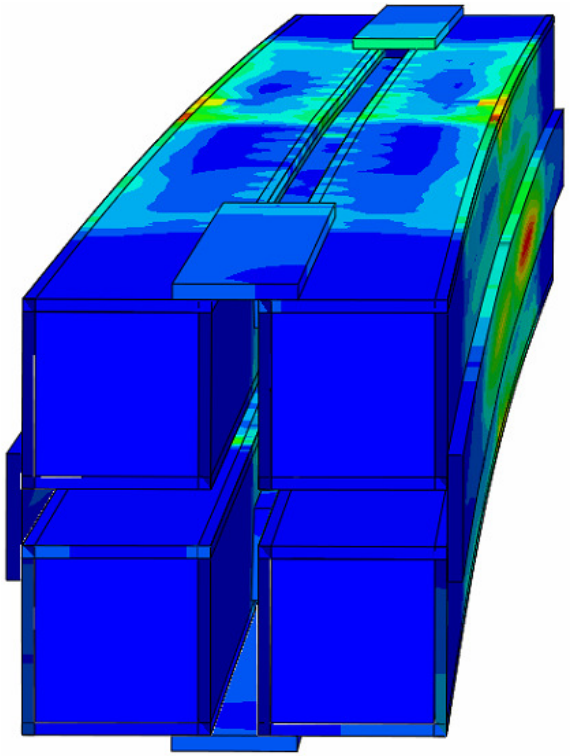
Dezvoltarea BRB-urilor „uscate" de 300 kN

Soluția finală:

- Țevile umplute cu beton.
- Performanța îmbunătățită, $\beta = 1.25$.

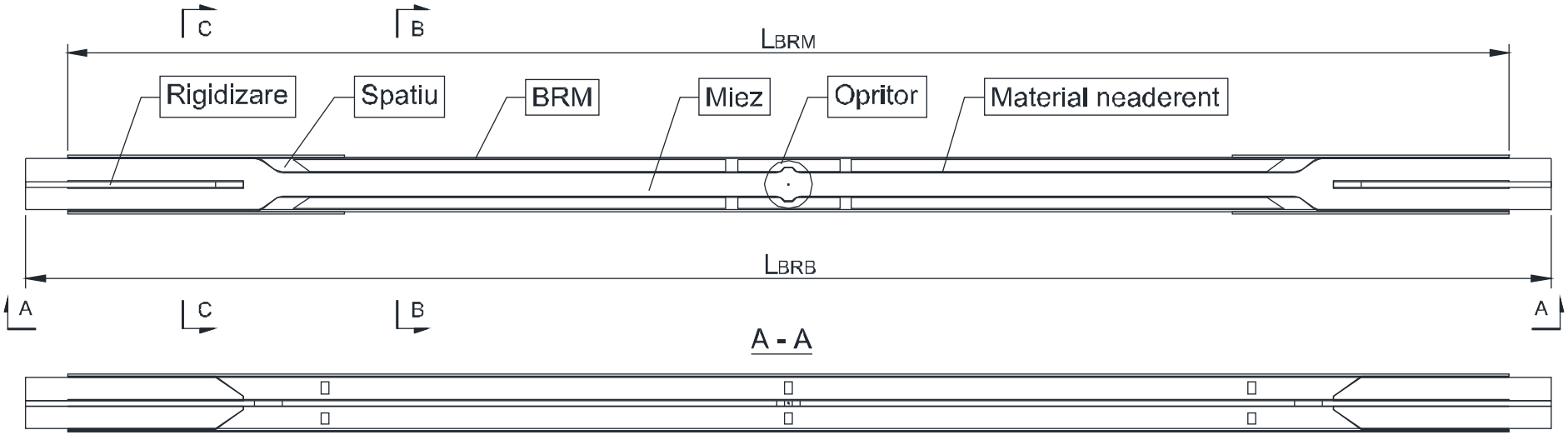


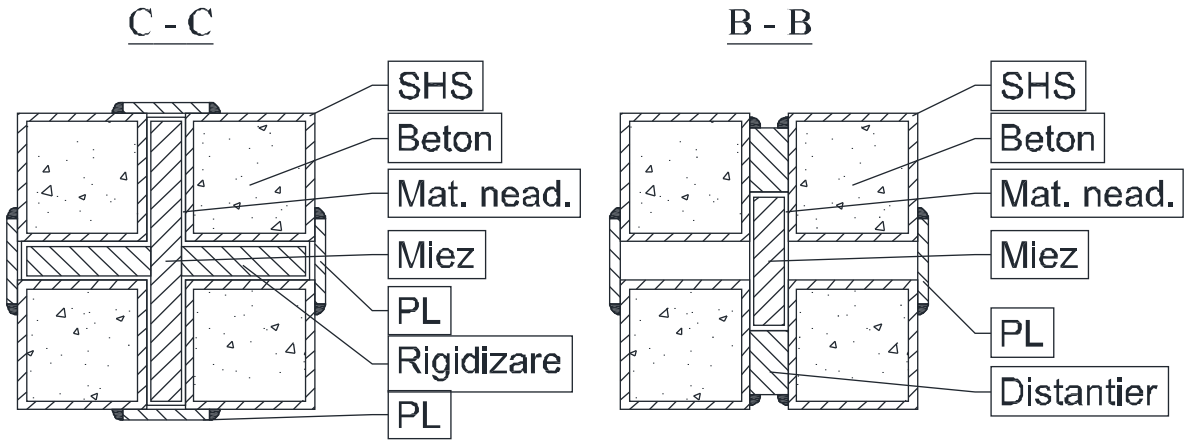




Soluția finală BRB 300kN „uscat”

Concept 3-a (300 kN): BRM = 4 SHS + beton

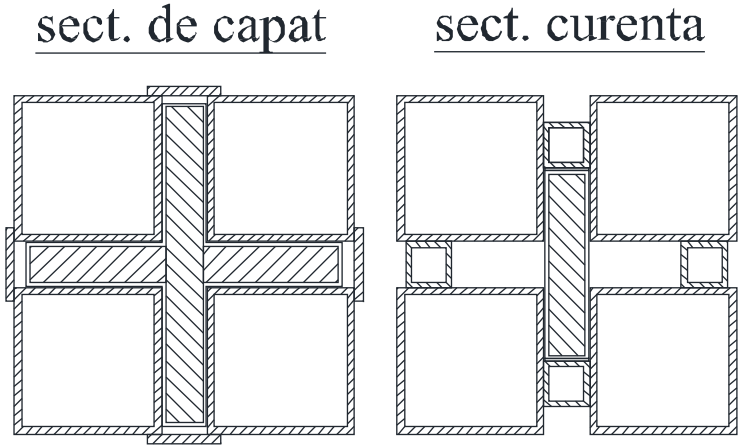


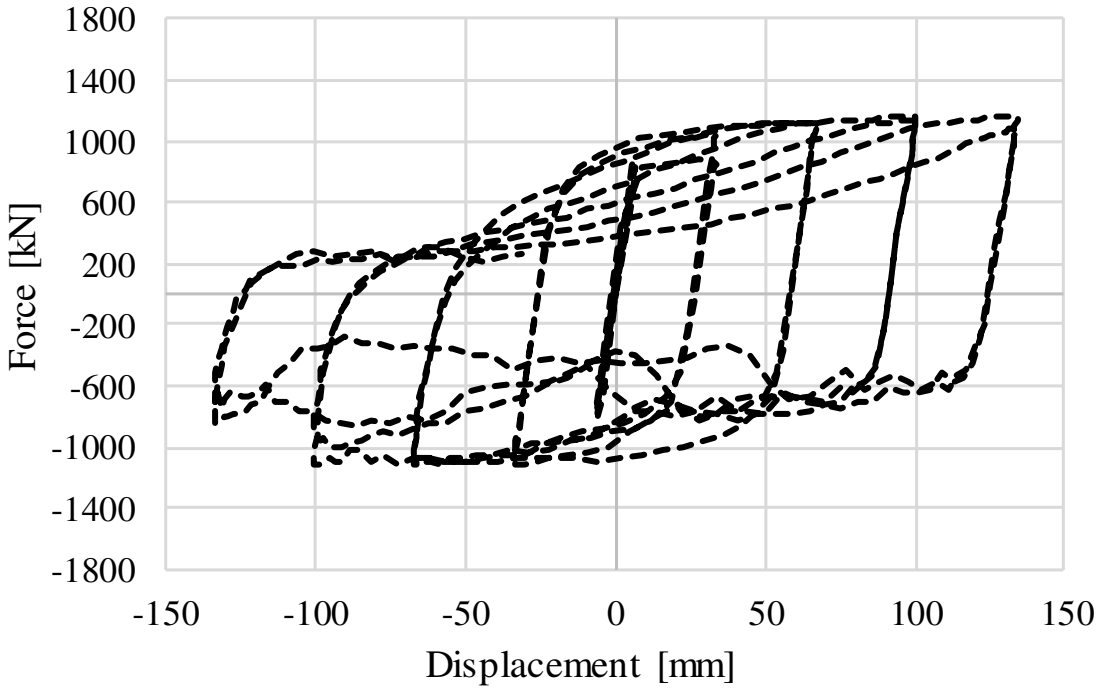


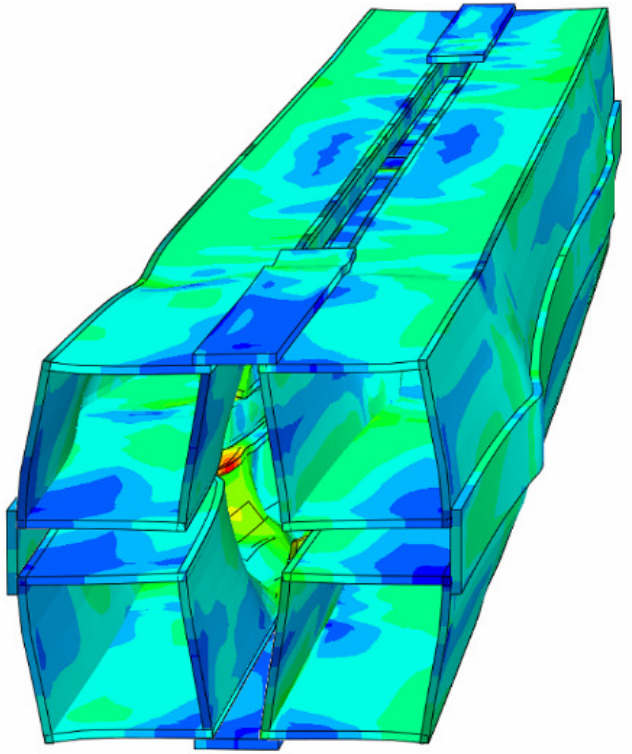
Dezvoltarea BRB-urilor „uscate" de 700 kN

Soluția inițială:

- BRB: comportare ciclică slabă.
- BRM:
  - Voalarea locală a pereților SHS.
  - Comportare globală acceptabilă.



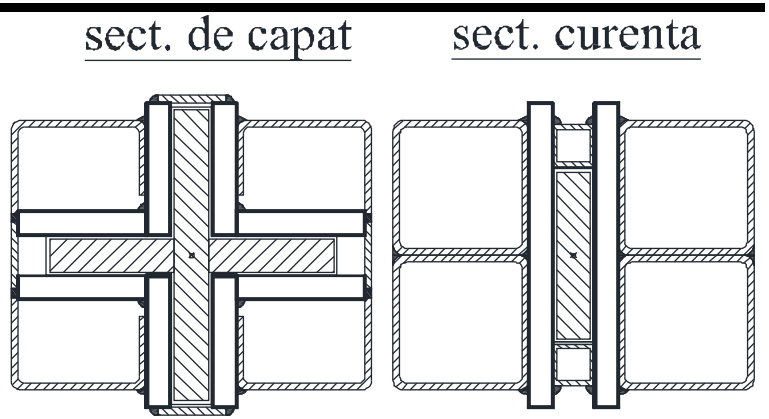


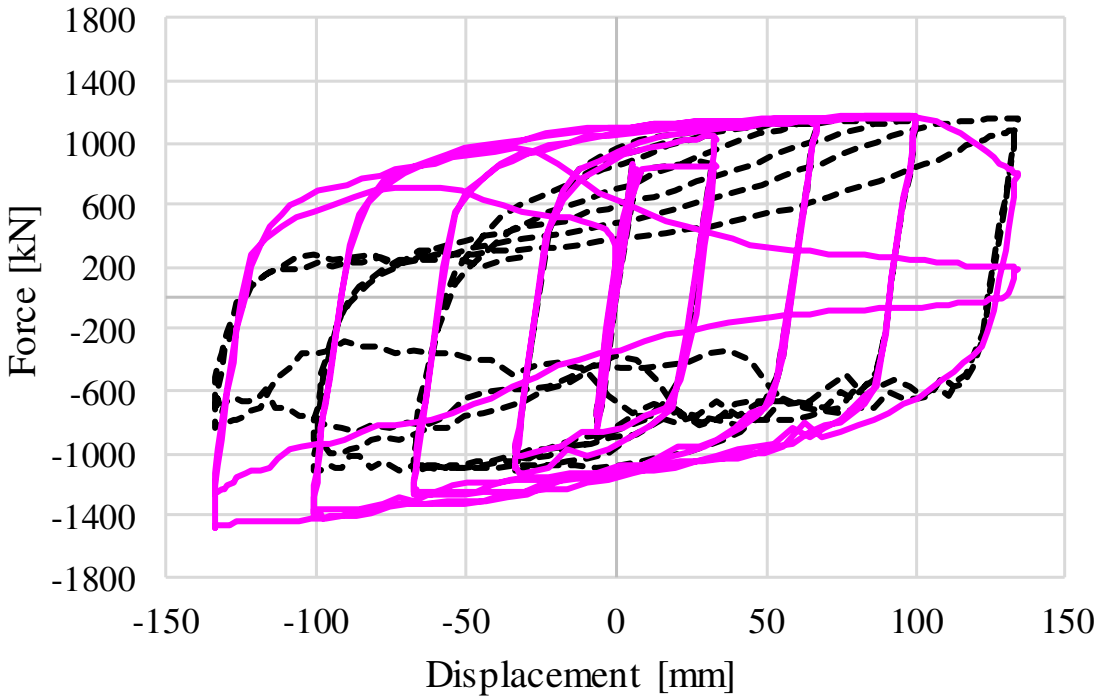


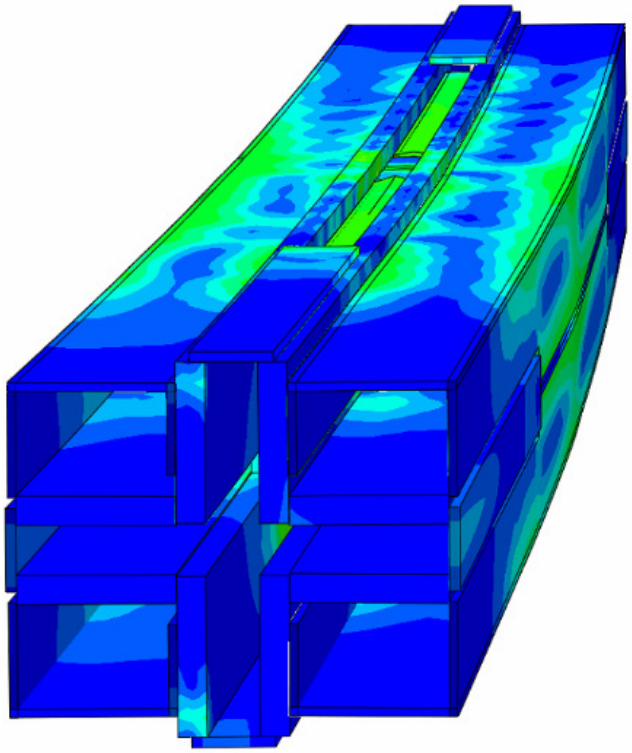
Dezvoltarea BRB-urilor „uscate" de 700 kN

Soluția finală:

- Platbenzi suplimentare din oțel.
- Performanța îmbunătățită, $\beta = 1.26$.

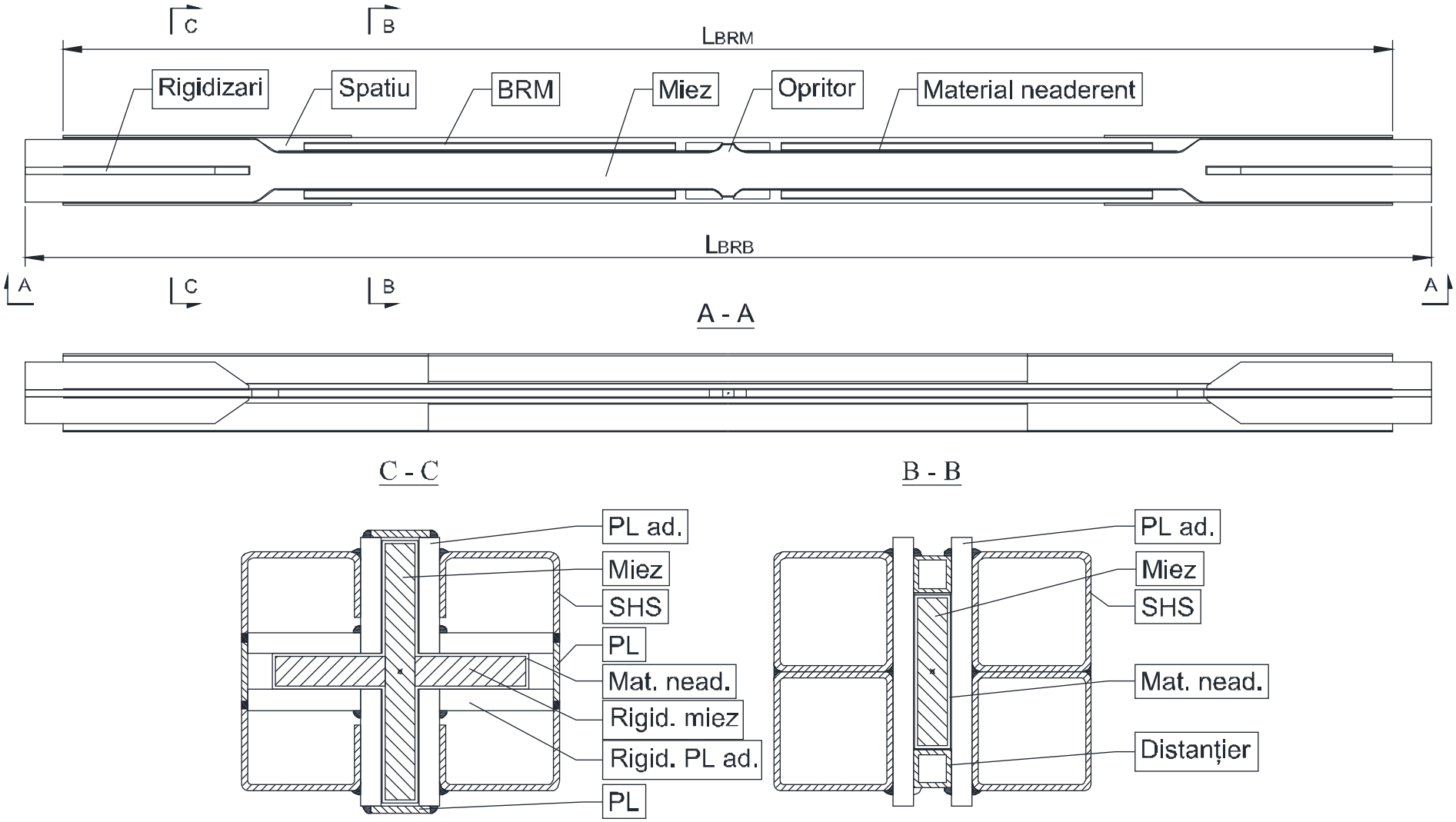






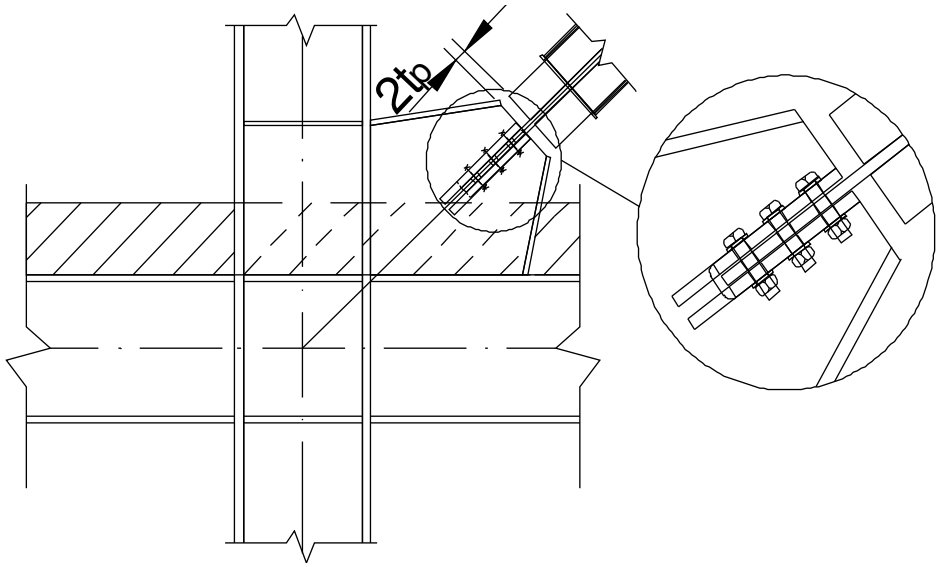
Soluția finală BRB 700kN „uscat”

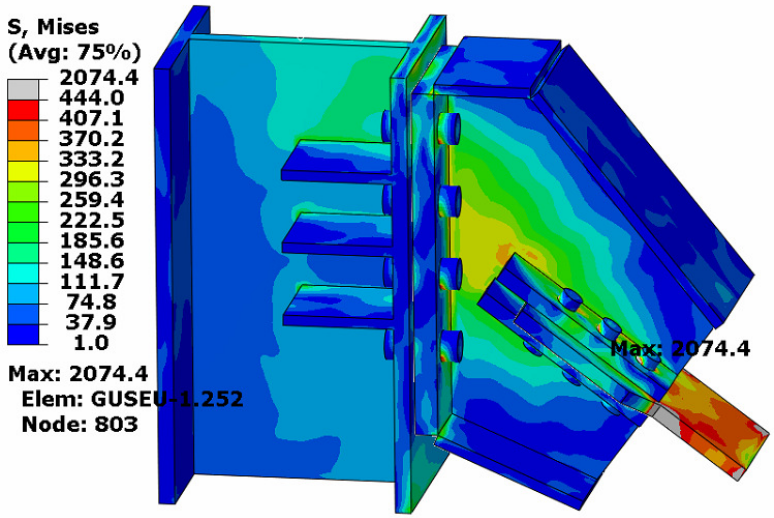
Concept 3-b (700 kN): BRM = 4 SHS + 2 platbenzi ranforsate

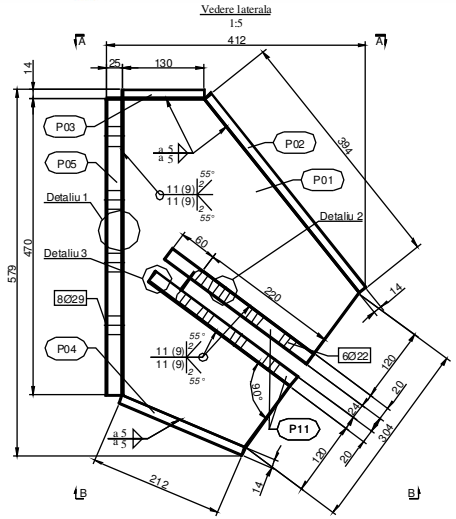


Zona de îmbinare a BRB-ului

- **Dezvoltarea conceptuală: îmbinare cu șuruburi**
- **Analiza numerică cu MEF (pentru stand)**







Încercări experimentale

Programul experimental

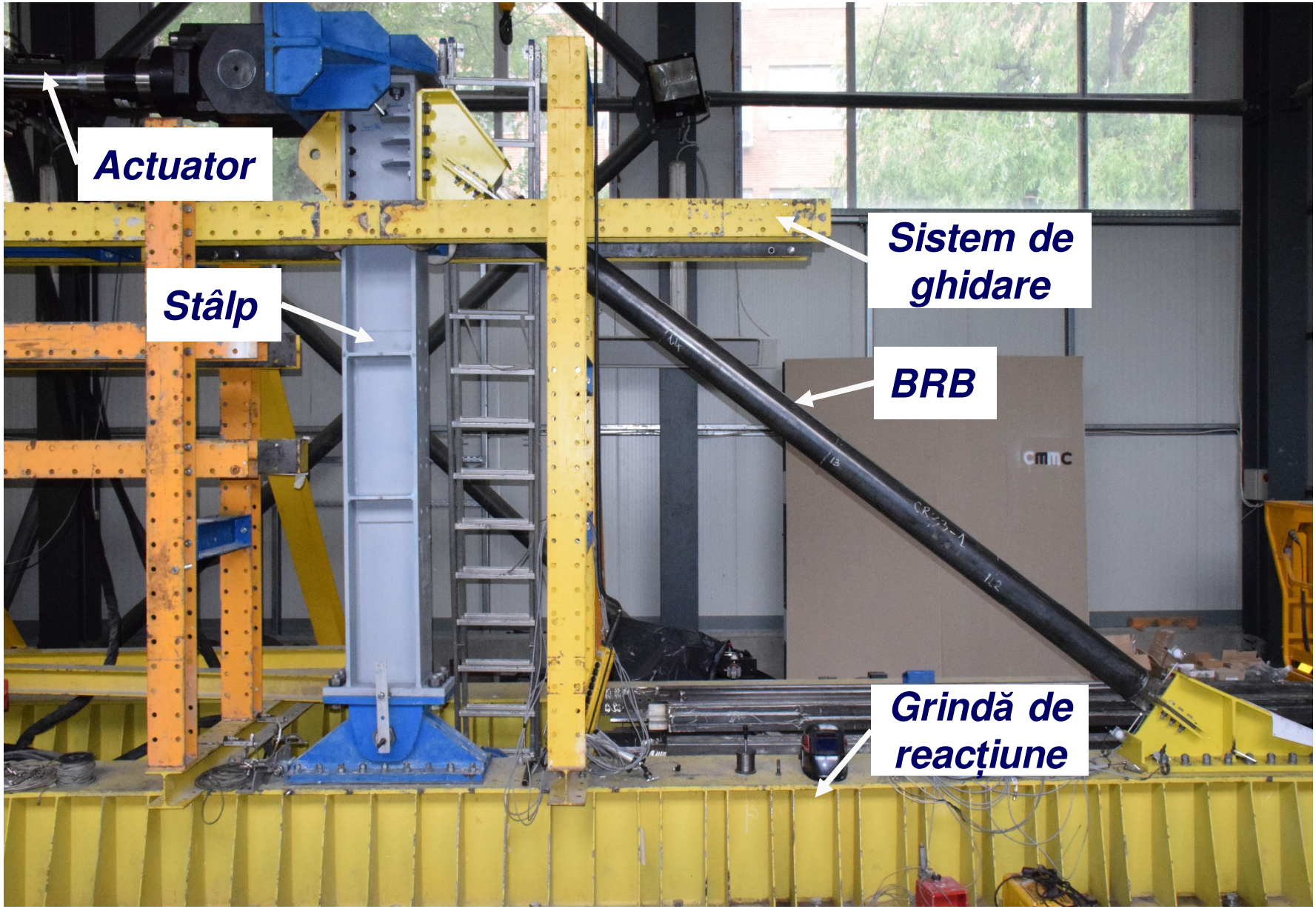
Pre-calificarea unui set de BRB-uri:

- Capacități încercate: 300 kN & 700 kN
- Plaja de capacități acoperită: 150 kN – 840 kN
- Pretabile pentru clădiri cu înălțime mică și medie
- 14 specimene: 10 ”convenționale” & 4 ”uscate”

Programul experimental

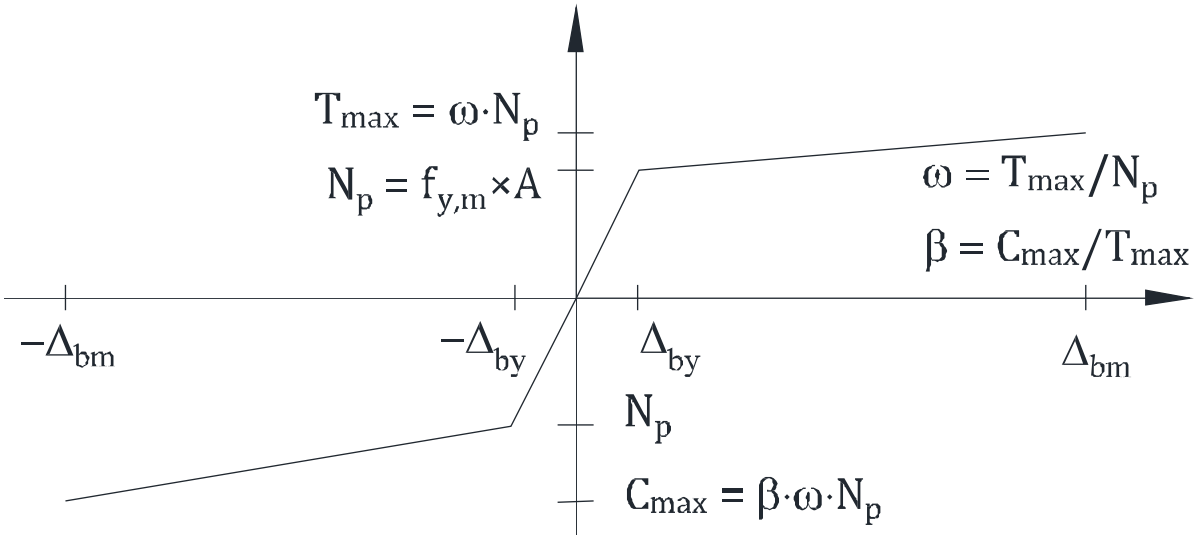
BRB	"convențional"					"uscat"	
Rezistența nominală	300 kN	700 kN	300 kN	700 kN	700 kN	300 kN	700 kN
N_{cr}/N_{pl}	3	3	3	3	1.5	3	3
Secțiunea transversală	14x60	20x99	30x30	45x45	20x99	14x60	20x99
ID specimen	CR33-1	CR73-1	CS33-1	CS73-1	CR71-1	DR33-1	DR73-1
	CR33-2	CR73-2	CS33-2	CS73-2	CR71-2	DR33-2	DR73-2

Standul experimental



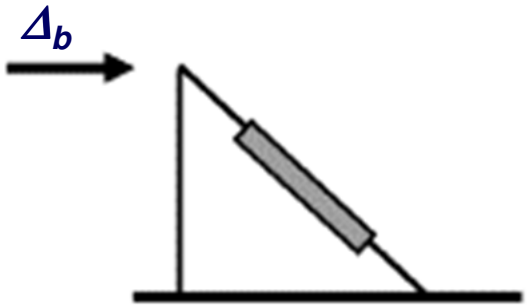
Procedura de calificare experimentală

- **Cerințe de precalificare:**
  - **specimenele demonstrează o comportare ciclică stabilă;**
  - **nu are loc ruperea miezului, flambajul global al BRB-ului, sau cedarea îmbinărilor;**
  - **pentru toate ciclurile la deformații mai mari de Δ_{by}, C_{max} & $T_{max} \geq N_p$;**
  - **pentru toate ciclurile la deformații mai mari de Δ_{by} , $C_{max}/T_{max} \leq 1{,}3$.**



Procedura de calificare experimentală

- **Schema subansamblului (P100-1/2013).**



- **Satisfacerea protocolului (10 cicluri)**
  - **2 cicluri de deformare la $\Delta_b = \Delta_{by}$**
  - **2 cicluri de deformare la $\Delta_b = 0{,}5\Delta_{bm}$**
  - **2 cicluri de deformare la $\Delta_b = 1{,}0\Delta_{bm}$**
  - **2 cicluri de deformare la $\Delta_b = 1{,}5\Delta_{bm}$**
  - **2 cicluri de deformare la $\Delta_b = 2{,}0\Delta_{bm}$**

  } CID ≥ 200 Δ_{by}

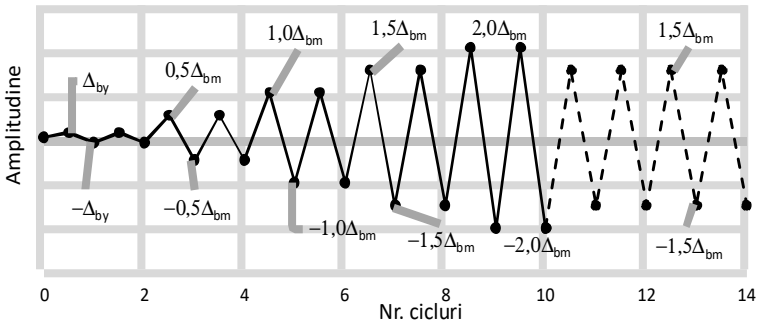
  - **cicluri suplimentare de deformare (dacă e cazul) la $\Delta_b = 1{,}5\Delta_{bm}$, până la atingerea unei deformații inelastice cumulative (CID) de cel puțin 200 Δ_{by}.**

Δ_{by} = valoarea deformației specimenului la curgere;

Δ_{bm} = dublul deplasării relative de nivel de calcul la starea limită ultimă, SLU, dar nu mai puțin de 2% din înălțimea de etaj

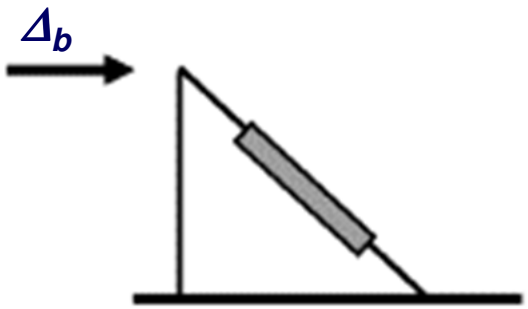
- **Coeficientul β:**
  $1{,}0 \leq \beta \leq 1{,}3$

- **Deformația inelatică cumulativă:**
  CID ≥ 200 Δ_{by}



Procedura utilizată

- **Schema subansamblului (P100-1/2013).**



- **Satisfacerea protocolului (10 cicluri)**
  - 2 cicluri de deformare la $\Delta_b = \Delta_{by}$
  - 2 cicluri de deformare la $\Delta_b = 0{,}5\Delta_{bm}$
  - 2 cicluri de deformare la $\Delta_b = 1{,}0\Delta_{bm}$
  - 2 cicluri de deformare la $\Delta_b = 1{,}5\Delta_{bm}$
  - 2 cicluri de deformare la $\Delta_b = 2{,}0\Delta_{bm}$

  } CID ≥ 200 Δ_{by}

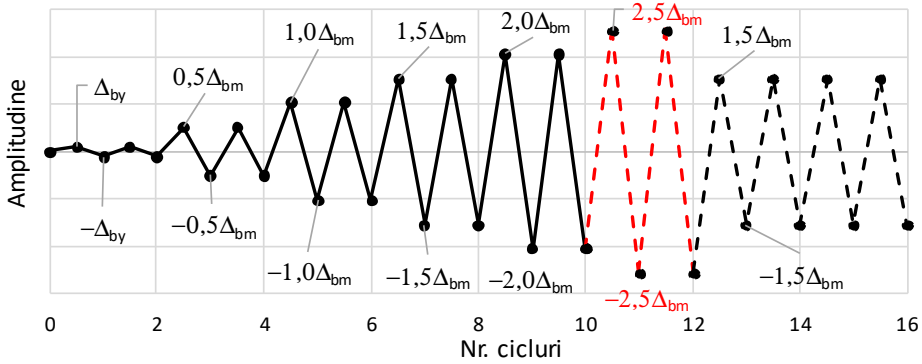
  - 2 cicluri de deformare la $\Delta_b = 2{,}5\Delta_{bm}$
  - cicluri suplimentare de deformare la $\Delta_b = 1{,}5\Delta_{bm}$, până la cedare.

Δ_{by} = valoarea deformației specimenului la curgere;

Δ_{bm} = dublul deplasării relative de nivel de calcul la starea limită ultimă, SLU, dar nu mai puțin de 2% din înălțimea de etaj

- **Coeficientul β:**
  $1{,}0 \leq \beta \leq 1{,}3$

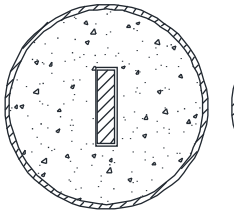
- **Deformația inelatică cumulativă:**
  CID ≥ 200 Δ_{by}



CR33 - BRB 300 kN

- **Protocol $2\Delta_{bm}$: îndeplinit 2/2**

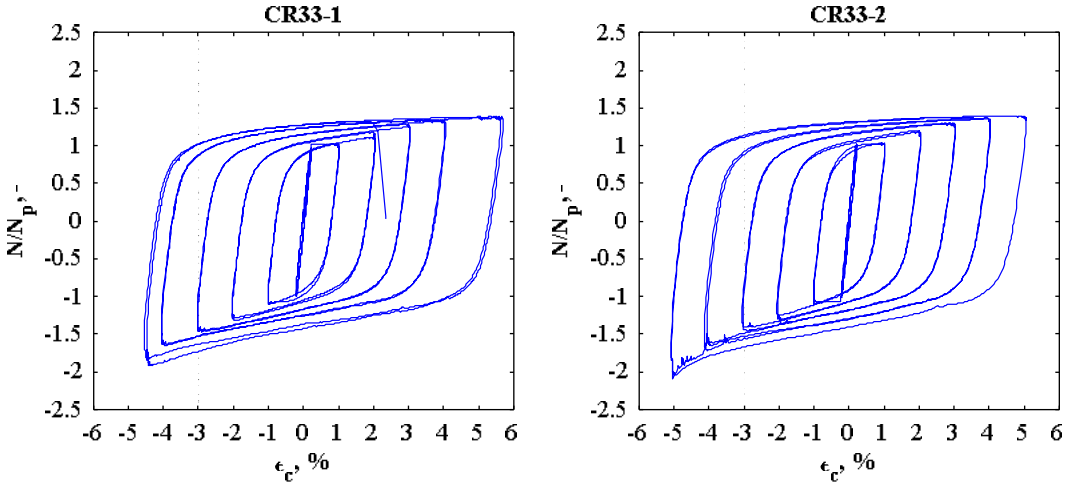
CR33



	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
CR33-1	1,35	1,23	4,05	≥ 200	comportare ciclică stabilă
CR33-2	1,37	1,22	4,04	≥ 200	comportare ciclică stabilă

- **Cicluri suplimentare**

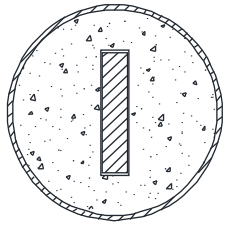
	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
CR33-1	1,39	1,38	4,53	≥ 200	cedare @ $1{,}5\Delta_{bm}$.1+ (12,25 cicluri)
CR33-2	1,40	1,49	5,06	≥ 200	cedare @ $1{,}5\Delta_{bm}$.1+ (11,75 cicluri)



CR71 - BRB 700 kN

- **Protocol $2\Delta_{bm}$: îndeplinit 1/2**

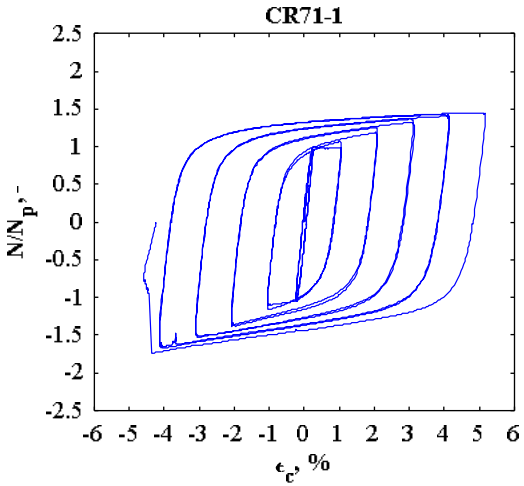
CR71

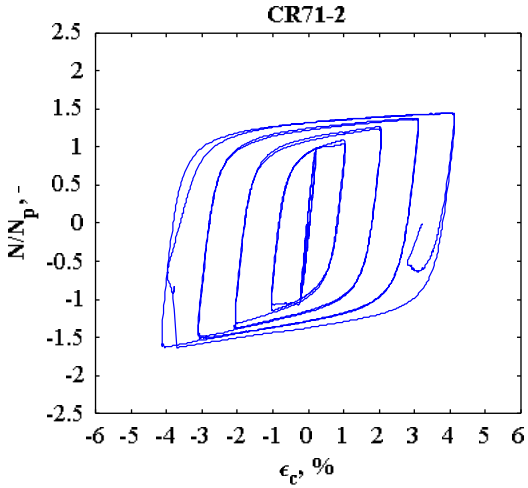


	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
CR71-1	1,43	1,15	4,14	≥ 200	comportare ciclică stabilă
CR71-2	1,45	1,12	4,13	≥ 200	flambaj global în plan @ 2,0Δ_{bm}.2- (9,25 cicluri)

- **Cicluri suplimentare**

	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
CR71-1	1,45	1,20	4,58	≥ 200	flambaj global în plan @ 2,5Δ_{bm}.1- (10,75 cicluri)
CR71-2	-	-	-	-	-





CR73 - BRB 700 kN

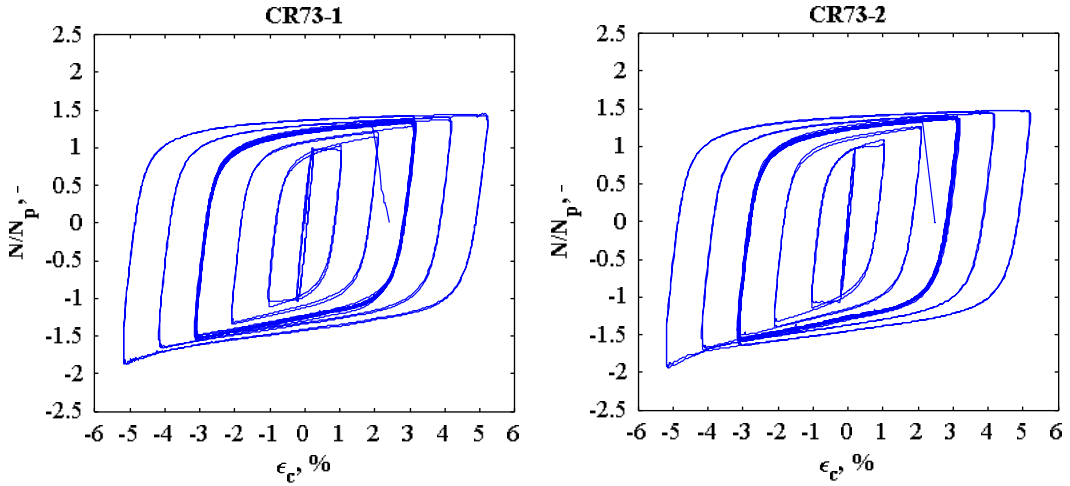
- **Protocol $2\Delta_{bm}$: îndeplinit 2/2**

CR73

	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
CR73-1	1,40	1,17	4,16	≥ 200	comportare ciclică stabilă
CR73-2	1,44	1,18	4,17	≥ 200	comportare ciclică stabilă

- **Cicluri suplimentare**

	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
CR73-1	1,45	1,30	5,19	≥ 200	cedare @ $1{,}5\Delta_{bm}$.14+ (25,25 cicluri)
CR73-2	1,48	1,31	5,20	≥ 200	cedare @ $1{,}5\Delta_{bm}$.14+ (25,75 cicluri)



CS33 - BRB 300 kN

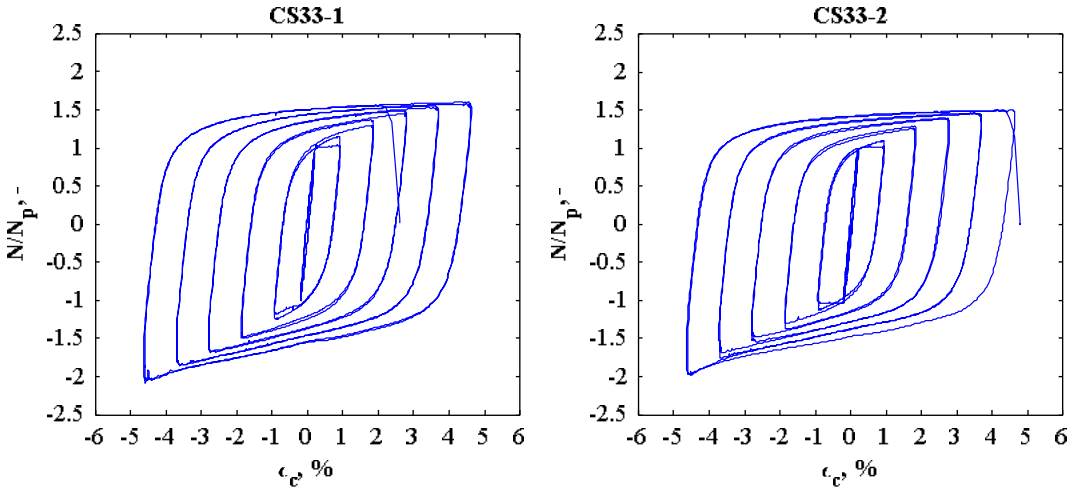
- **Protocol $2\Delta_{bm}$: îndeplinit 2/2**

CS33

	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
CS33-1	1,56	1,19	3,69	≥ 200	comportare ciclică stabilă
CS33-2	1,46	1,20	3,70	≥ 200	comportare ciclică stabilă

- **Cicluri suplimentare**

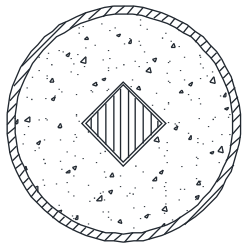
	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
CS33-1	1,60	1,30	4,62	≥ 200	cedare @ $1{,}5\Delta_{bm}$.1+ (12,25 cicluri)
CS33-2	1,50	1,32	4,64	≥ 200	cedare @ $2{,}5\Delta_{bm}$.2+ (11,75 cicluri)



CS73 - BRB 700 kN

- **Protocol $2\Delta_{bm}$: îndeplinit 1/2**

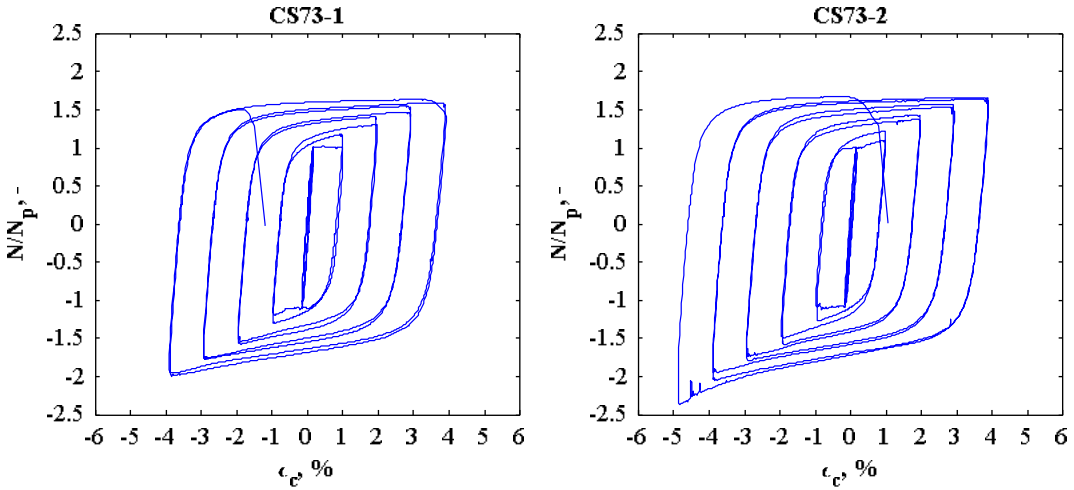
CS73



	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
CS73-1	1,64	1,22	3,90	≥ 200	cedare @ $2\Delta_{bm}$.2- (9,75 cicluri) <- impef. ax.miez
CS73-2	1,66	1,23	3,88	≥ 200	comportare ciclică stabilă

- **Cicluri suplimentare**

	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
CS73-1	-	-	-	-	-
CS73-2	1,67	1,41	3,88	≥ 200	cedare @ $2,5\Delta_{bm}$.1+ (10,75 cicluri)

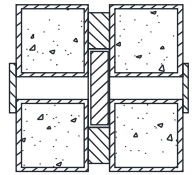


D33 - BRB 300 kN

- **Protocol $2\Delta_{bm}$: îndeplinit 0/2**

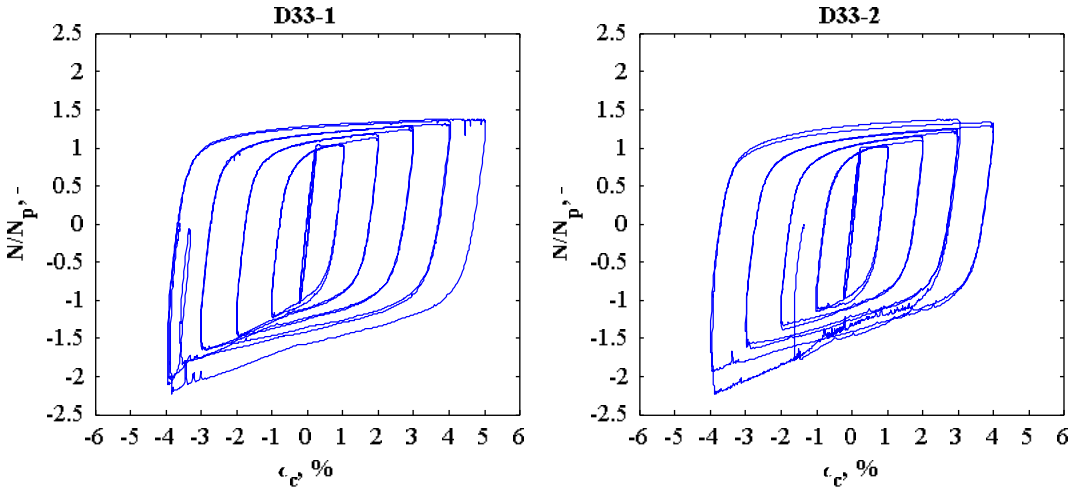
D33

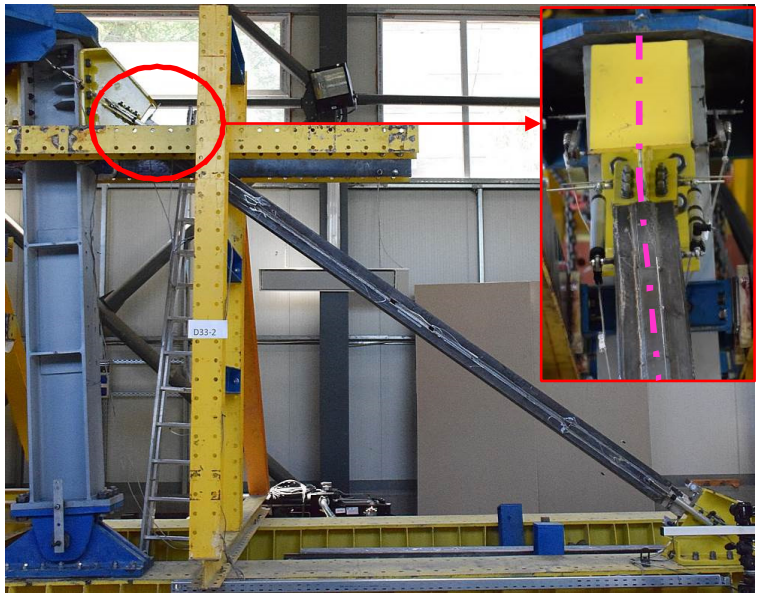
	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
D33-1	1,36	1,55	3,95	< 200	flambaj global _|_ plan @ 1,5Δ_{bm}.2- (7,50 cicluri)
D33-2	1,34	1,66	3,99	< 200	flambaj global _|_ plan @ 1,5Δ_{bm}.1- (6,50 cicluri)



- **Cicluri suplimentare**

	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
D33-1	-	-	-	-	-
D33-2	-	-	-	-	-

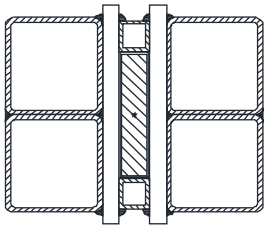




D73 - BRB 700 kN

- **Protocol $2\Delta_{bm}$: îndeplinit 2/2**

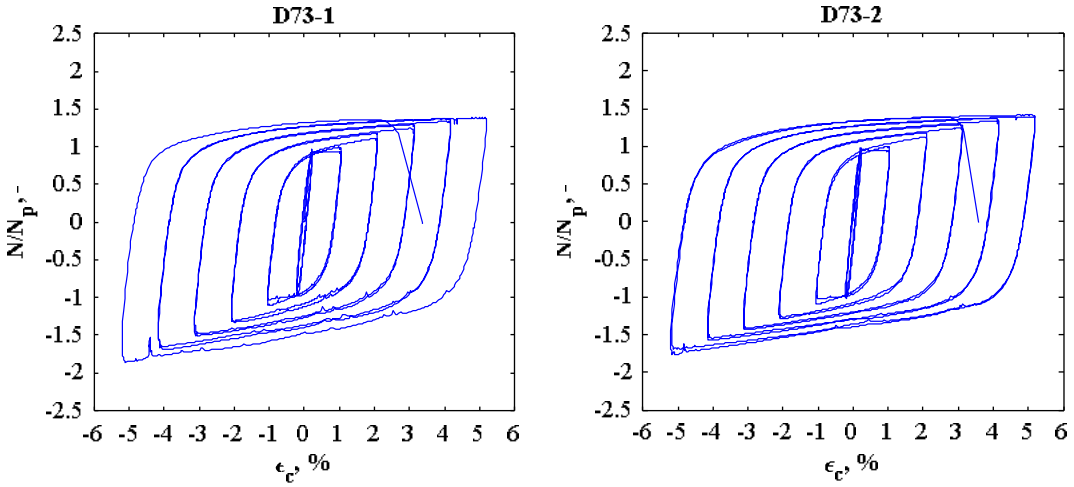
D73



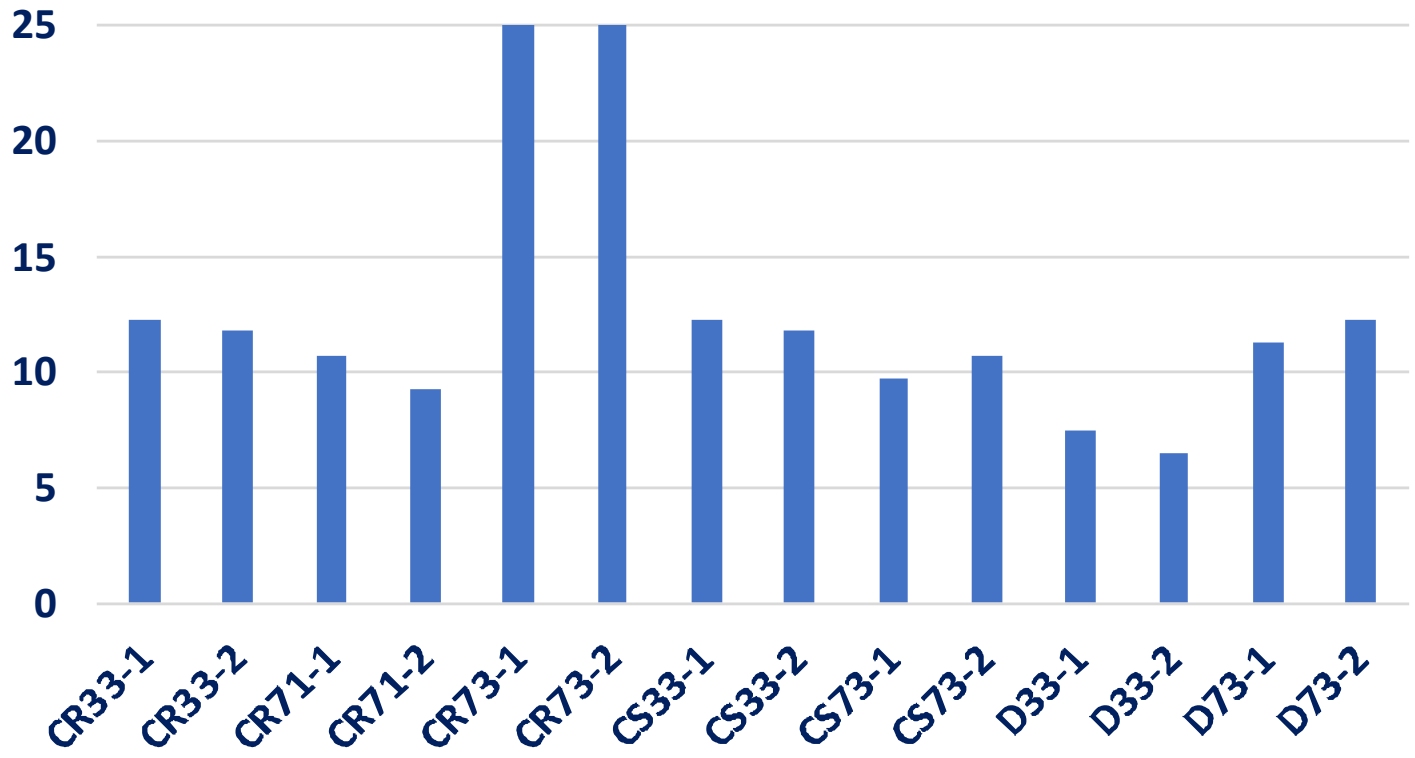
	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
D73-1	1,37	1,24	4,17	≥ 200	comportare ciclică stabilă
D73-2	1,37	1,15	4,16	≥ 200	comportare ciclică stabilă

- **Cicluri suplimentare**

	ω	β	ε_c [%]	CID/Δ_{by}	Observații:
D73-1	1,39	1,35	5,20	≥ 200	cedare @ $2{,}5\Delta_{bm}$.2+ (11,25 cicluri)
D73-2	1,42	1,24	5,19	≥ 200	cedare @ $1{,}5\Delta_{bm}$.1+ (12,25 cicluri)



Nr. de cicluri @ cedare



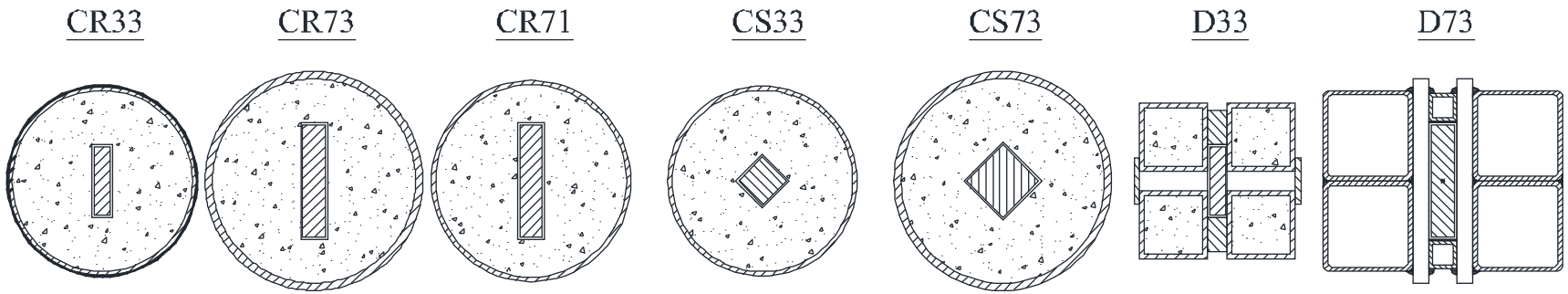
Sumar încercări experimentale

Soluția BRB	Tip	Miez	Formă	Ajustare N_p	Performanță	Tehnologie
CRx3	conv.	frezat	PL	DA	DA	DA
CRx1	conv.	frezat	PL	DA	NU	DA
CSx3	conv.	laminat+rigidizări	OP	NU	NU	NU
D33	mixt	frezat	PL	DA	NU	NU
D73	uscat	frezat	PL	DA	DA	NU

- Ajustarea N_p pe baza $f_{y,m}$
- Performanța ciclică – îndeplinirea condițiilor de calificare
- Tehnologia – simplitatea execuției &
  – insensibilitatea soluției la abaterile de execuție

Concluziile programului experimental

- **14 specimene, 5 soluții conceptuale**
  - **Soluția „convențională”, miez frezat & dreptunghiular, N_{cr}/N_p = 3: calificată (4/4 specimene)**
  - **Soluția „convențională”, miez frezat & dreptunghiular, N_{cr}/N_p =1,5: ne-calificată (1/2 specimene)**
  - **Soluția „convențională”, miez laminat + rigidizări, N_{cr}/N_p = 3: ne-calificată (3/4 specimene)**
  - **Soluția mixtă, miez frezat & dreptunghiular, N_{cr}/N_p = 3: ne-calificată (0/2 specimene)**
  - **Soluția „uscată”, miez frezat & dreptunghiular, N_{cr}/N_p = 3: calificată (2/2 specimene)**



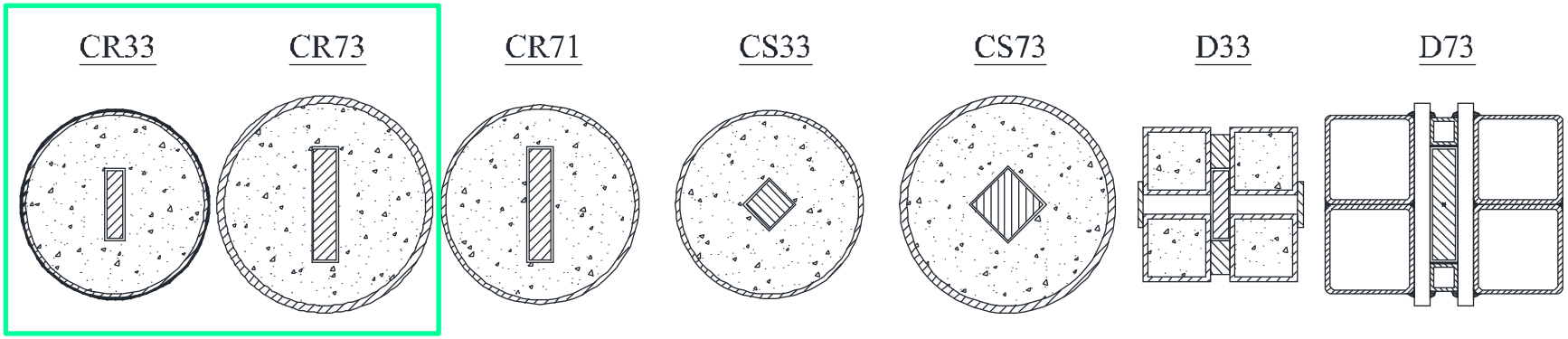
Concluziile programului experimental

- **Soluția optimă dpdv al performanței ciclice și al tehnologiei de fabricare:**

  BRB „convențional” cu miez frezat & dreptunghiular

- **Valori recomandate în proiectarea BRB-urilor:**
  - $\omega = 1{,}45$
  - $\omega\beta = 1{,}7 \Rightarrow \beta = 1{,}17$
  - $\varepsilon_{c,max} = \pm 4\%$

	@ $2D_{bm}$				@ cedare			
BRB	β	ω	ε_c	CID/Δ_{by}	β	ω	ε_c	CID/Δ_{by}
CR33-1	1.23	1.35	4.05	≥ 200	1.38	1.39	4.53	≥ 200
CR33-2	1.22	1.37	4.04	≥ 200	1.49	1.40	5.06	≥ 200
CR73-1	1.17	1.40	4.16	≥ 200	1.30	1.45	5.19	≥ 200
CR73-2	1.18	1.44	4.17	≥ 200	1.31	1.48	5.20	≥ 200



CR73-2 (26 cicluri @ cedare)