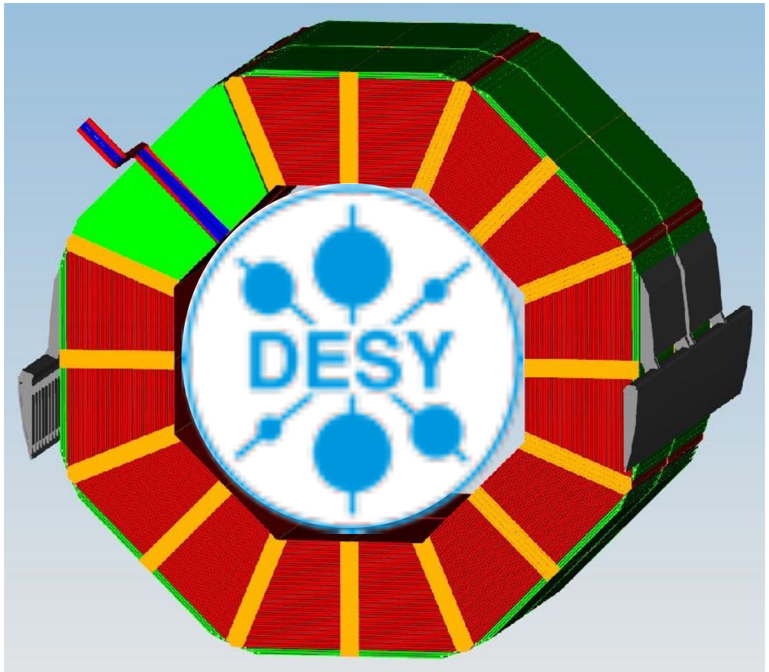
Towards a seismic stability validation of the AHCAL structure

Karsten Gadow, Martin Lemke, Felix Sefkow



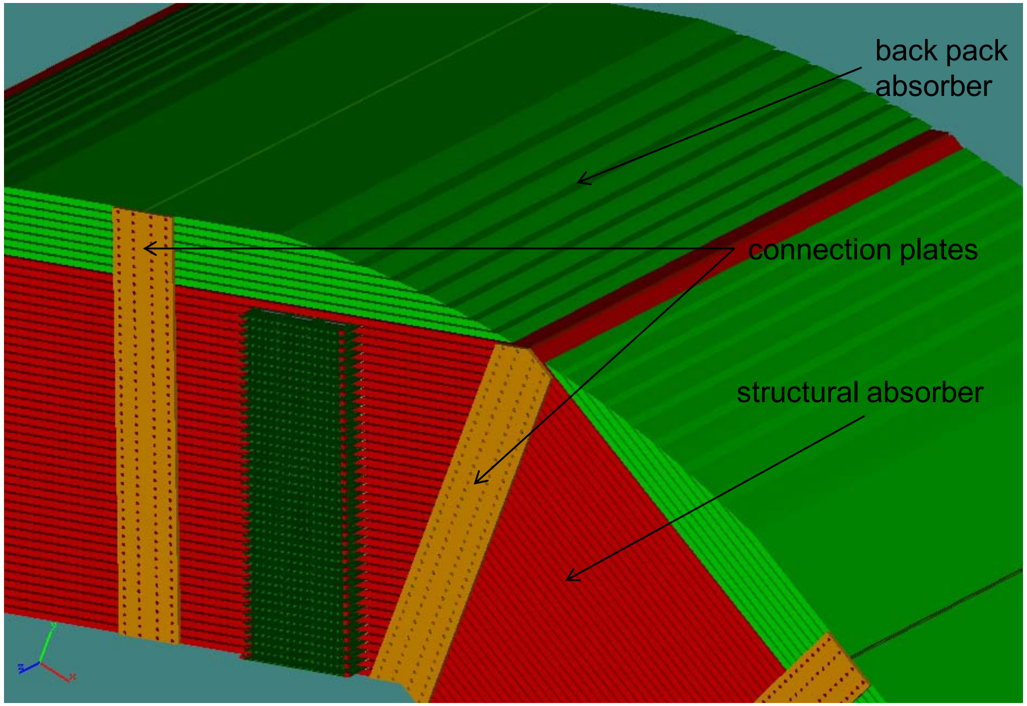
Mini-Workshop on ILC Infrastructure and CFS for Physics and Detectors
KEK, Tsukuba, May 16, 2017

Outline

- The AHCAL mechanical structure
- Static computations
- First steps dynamical analysis
- Methodological progress

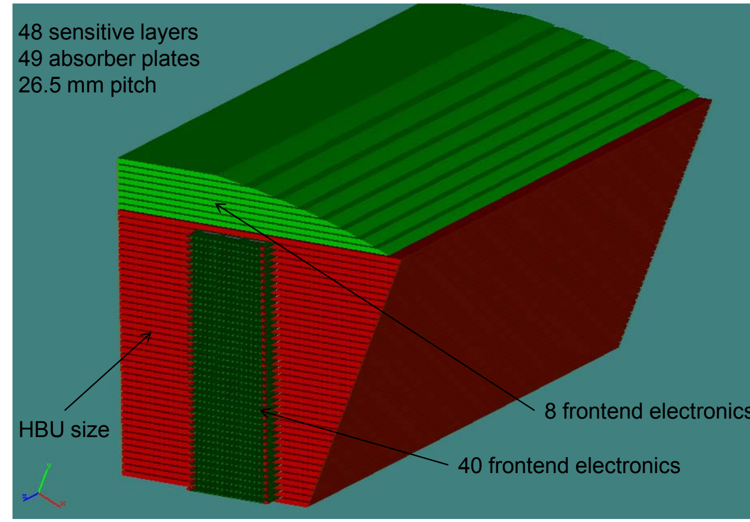
Design challenges

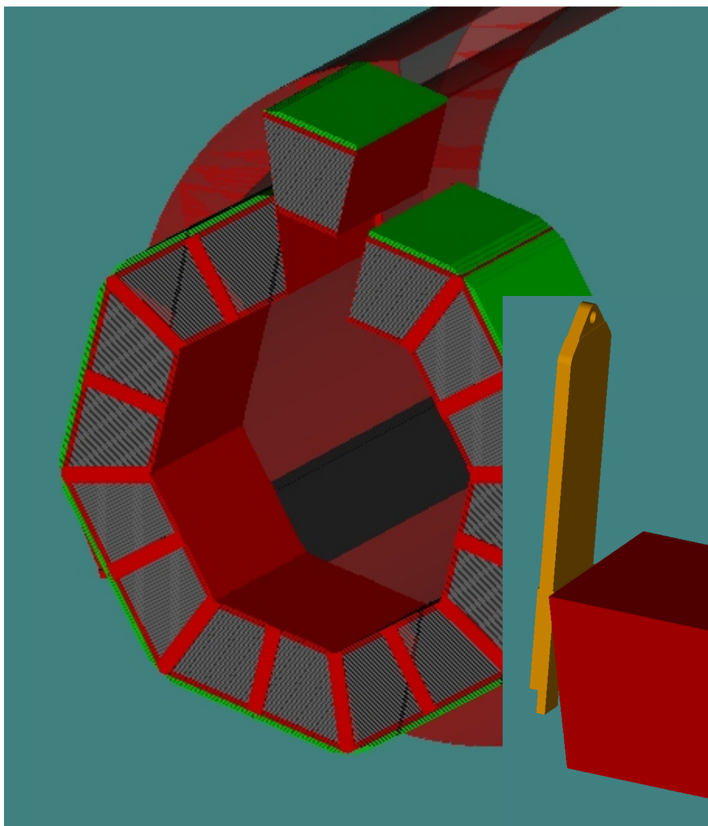
- Stainless steel
- Fine longitudinal sampling
  - 2cm plate thickness only
- No cracks, minimal un-instrumented regions
- Inside coil radius:
  - compact design to maximise no. of hadronic interaction lengths
  - tight tolerances over large dimensions
- Accessible electronics
  - external: short access
  - internal: longer shutdown or upgrade
- Earth quake stability
  - computational challenge

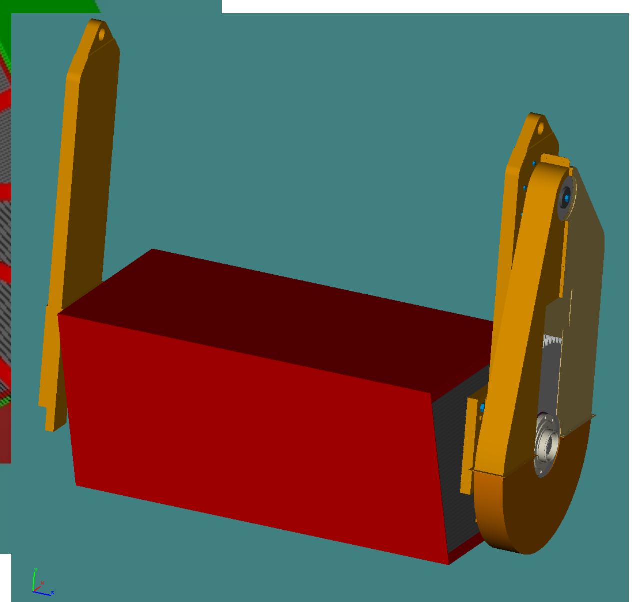


Small modules

- Small sectors (<18t) for easy transport and assembly in situ





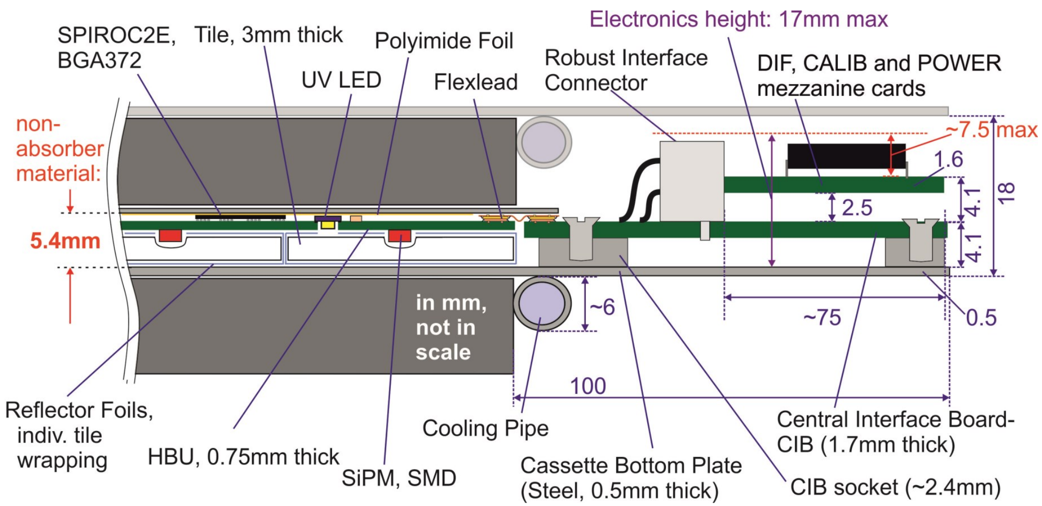


Design features

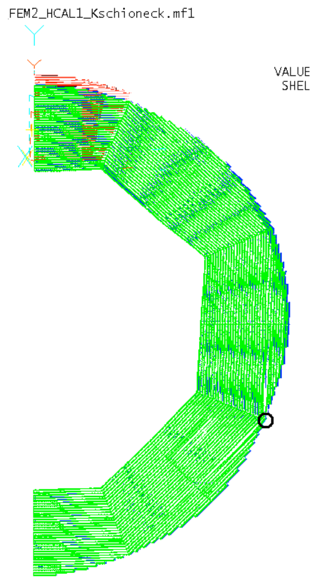
- Uniform sampling along shower axis
- Structure is made from rolled steel plates
  - flatness with roller levelling within 1mm verified
  - no machining: cost effective
- Assembly with screws
  - moderate tolerances
  - damping oscillations
- Thin side walls (5mm)
- 16 phi sectors, 2 rings
- Flexible structure, matched to flexibility of scintillator cassettes
- Varying layer width no problem for scintillator

Cassettes

- Housing the scintillator and electronics active layers
- Made from stainless steel and contributes to absorbing material
- Sum of absorber plate and cassette thickness = 20 m / layer
  - for both AHCAL and SDHCAL
  - material in absorber plate contributes to rigidity of structure
  - material in cassette contributes to load on structure
- AHCAL Physics prototype and early designs had 16 + 2x2 mm
- Present design and new prototype have 19 + 2x0.5 mm
- Weight is 17 kg /m2
  - cf SDHCAL 48 kg / m2 with 2x 2.5 mm cassette



Orientation



- Earlier studies have shown that the “roman arc” structure shows less deformation with a tip at the top than with a flat top
- However, this leads to a conflict with ECAL endcap module structure and square insert

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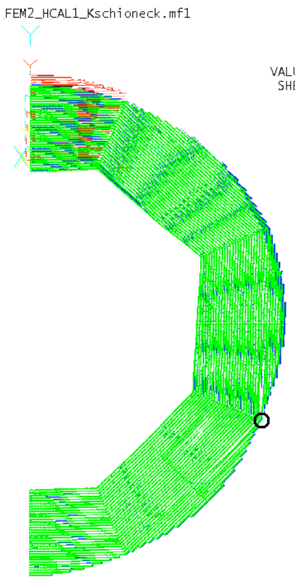

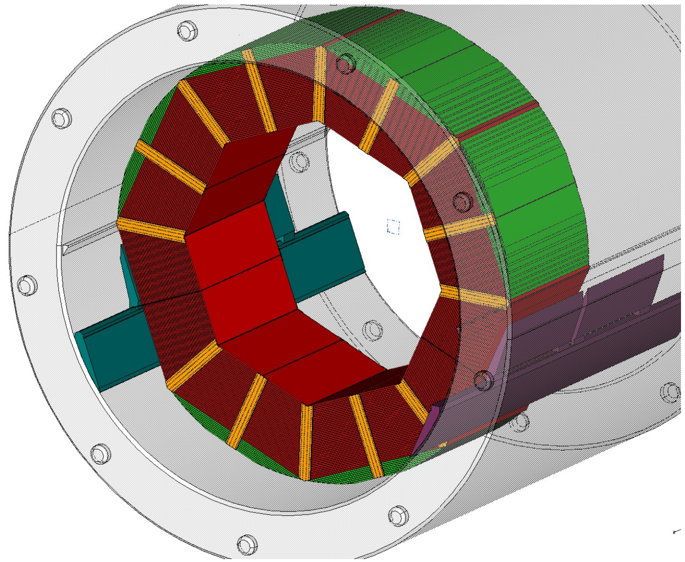

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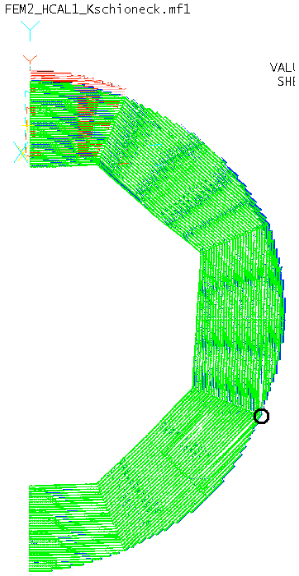

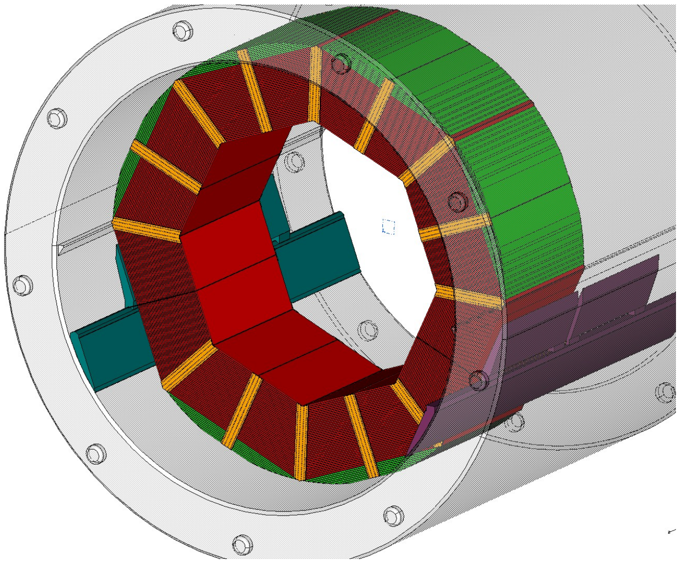

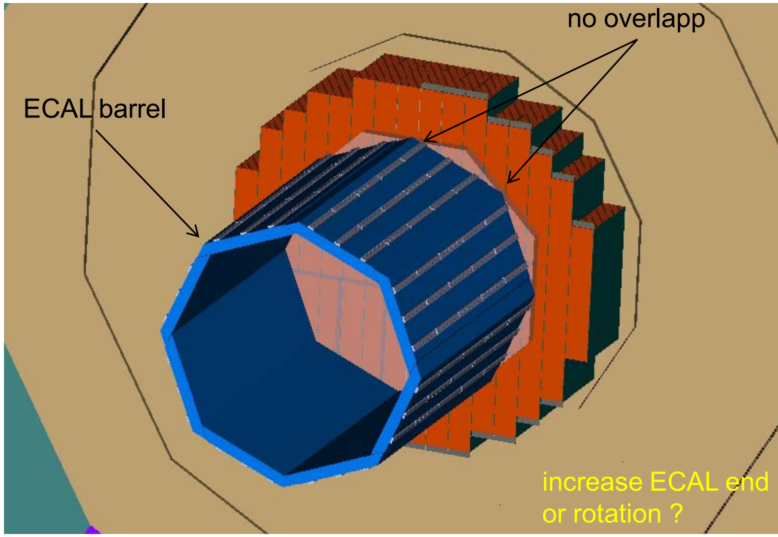

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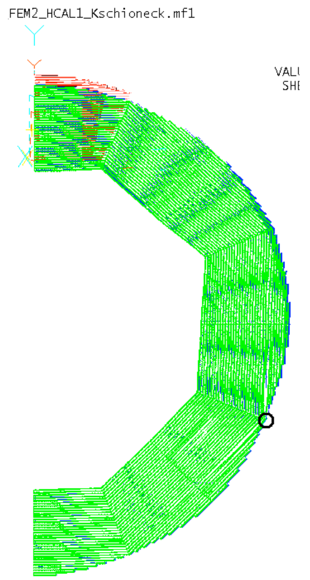

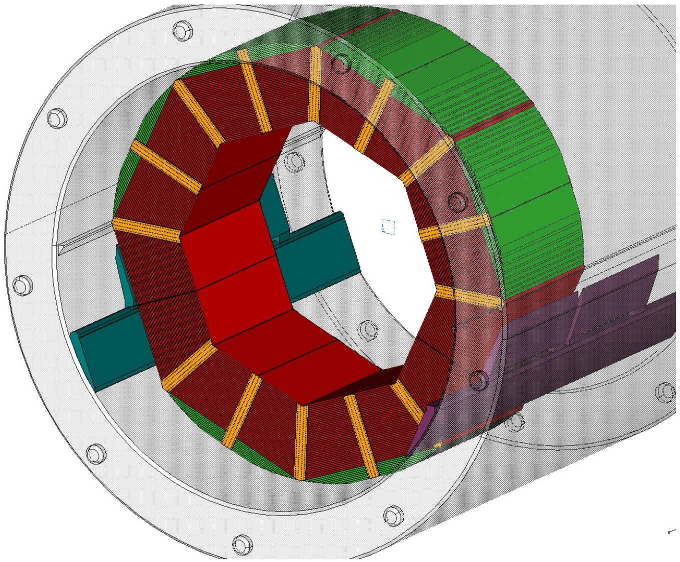

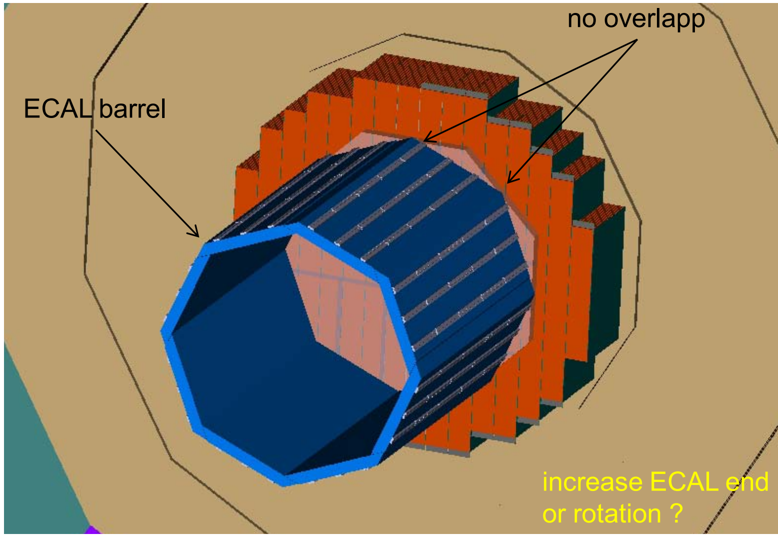

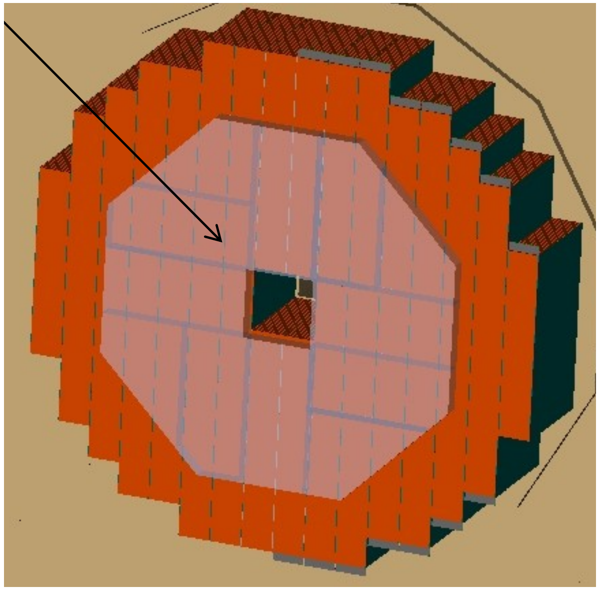

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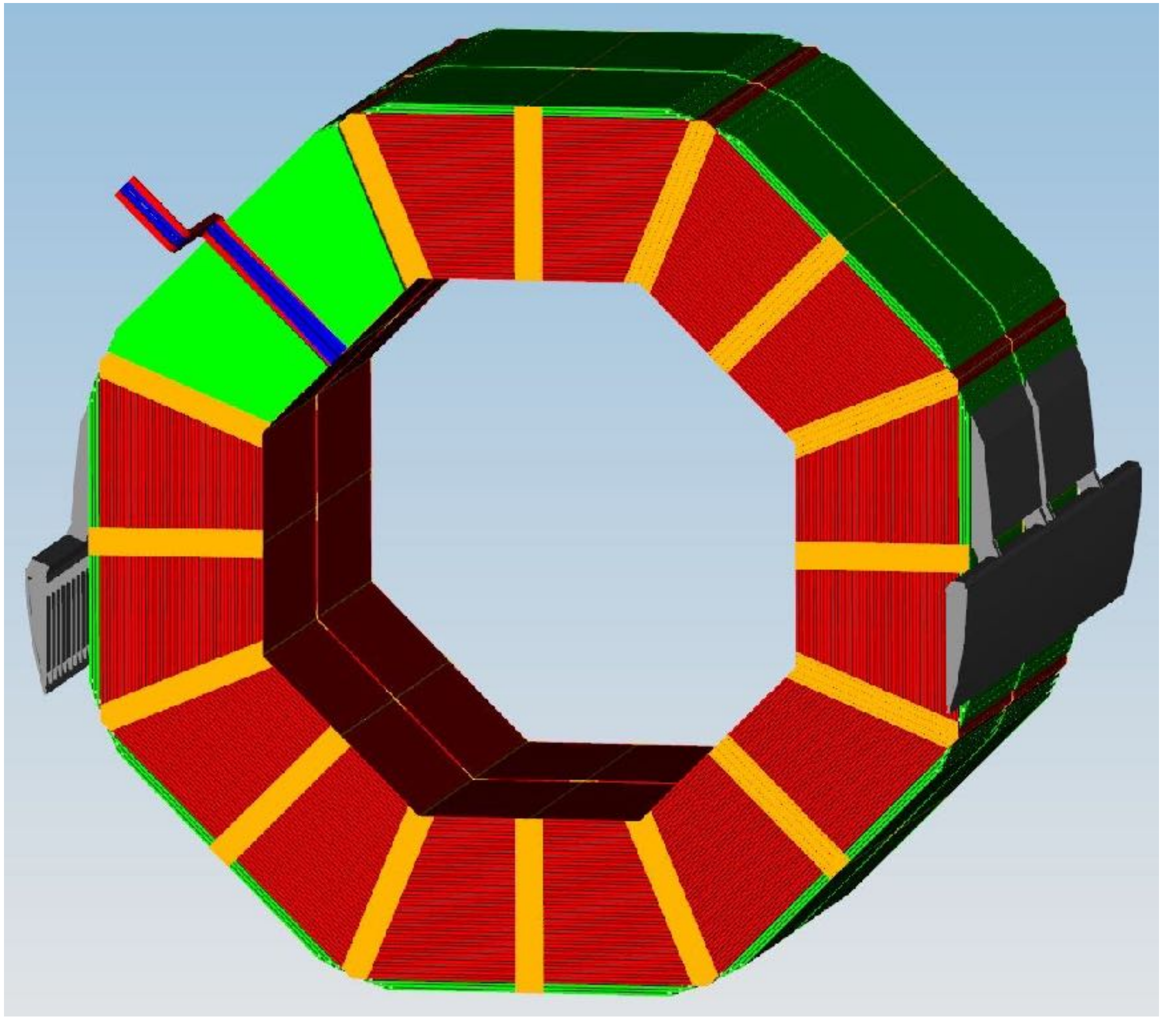
- However, this leads to a conflict with ECAL endcap module structure and square insert

Alternative

- Integration into cryostat done
- Stability calculation to be re-done
- Expect somewhat larger deformations
- On the other hand, stability improves with
  - up-to-date plate thickness
    - 16 -> 19mm
  - possibly even thicker plates
  - smaller radius



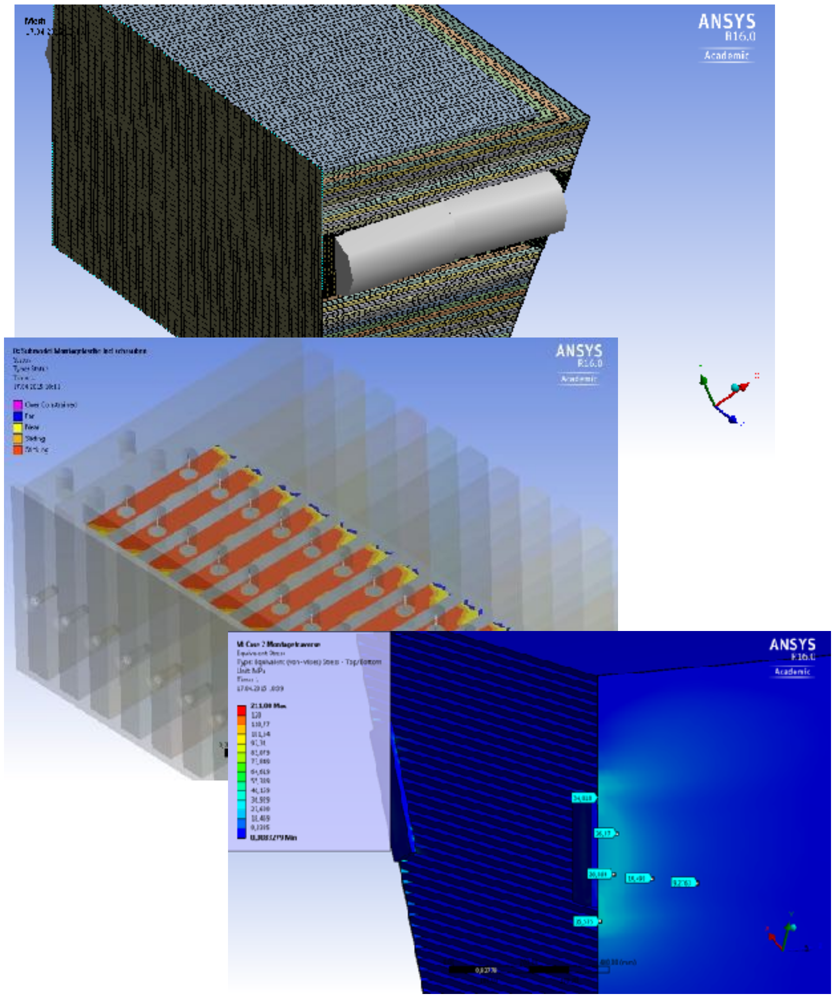
Stability: static calculations

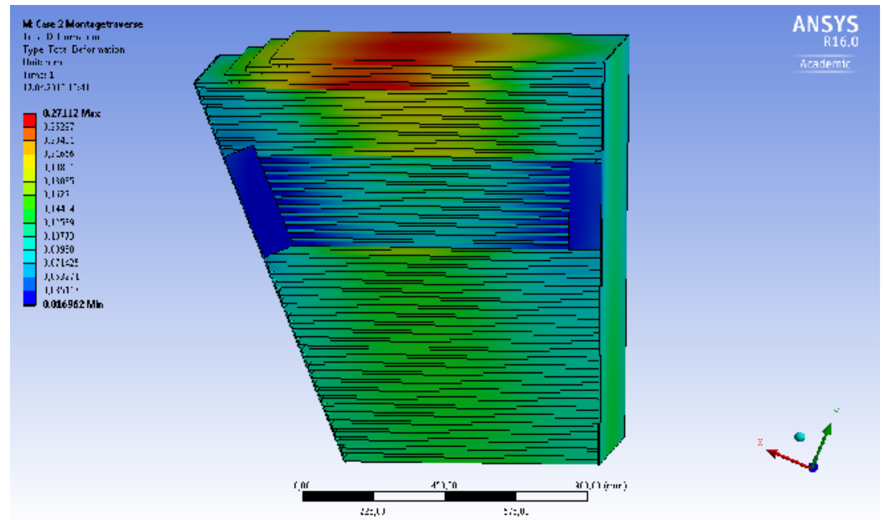
- Stability of modules for transportation and handling
- Stability of barrel structure - static

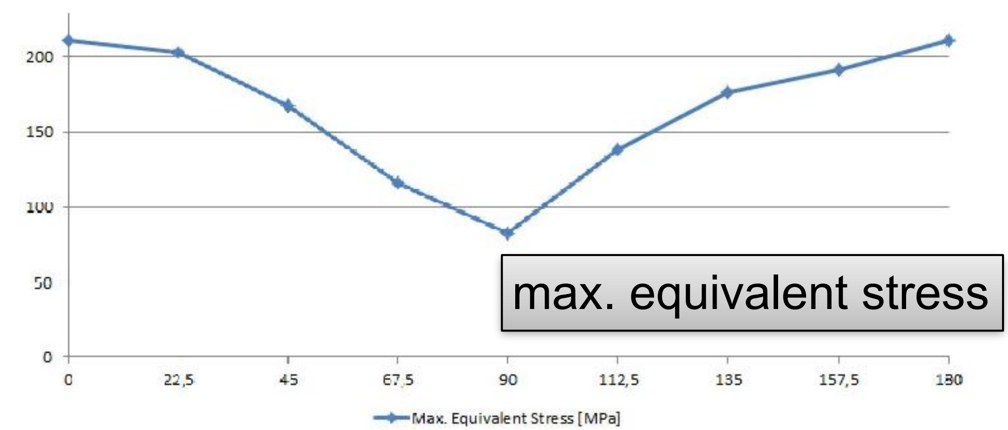
ANSYS model

- Parameters for submodule validations:
- Mesh types:
  - shell bodies for all plates
  - solid bodies for transportation and assembly brackets
- Mesh statistics:
  - ~ 575.000 nodes, 295.000 elements
  - refined local sub-models: 1.5M nodes, 870k elements
- Contacts:
  - bonded contacts (all DOF fixed) on lines and faces of shell bodies
  - bolts modelled as spring elements in refined sub-model in case of high load concentrations

Module installation

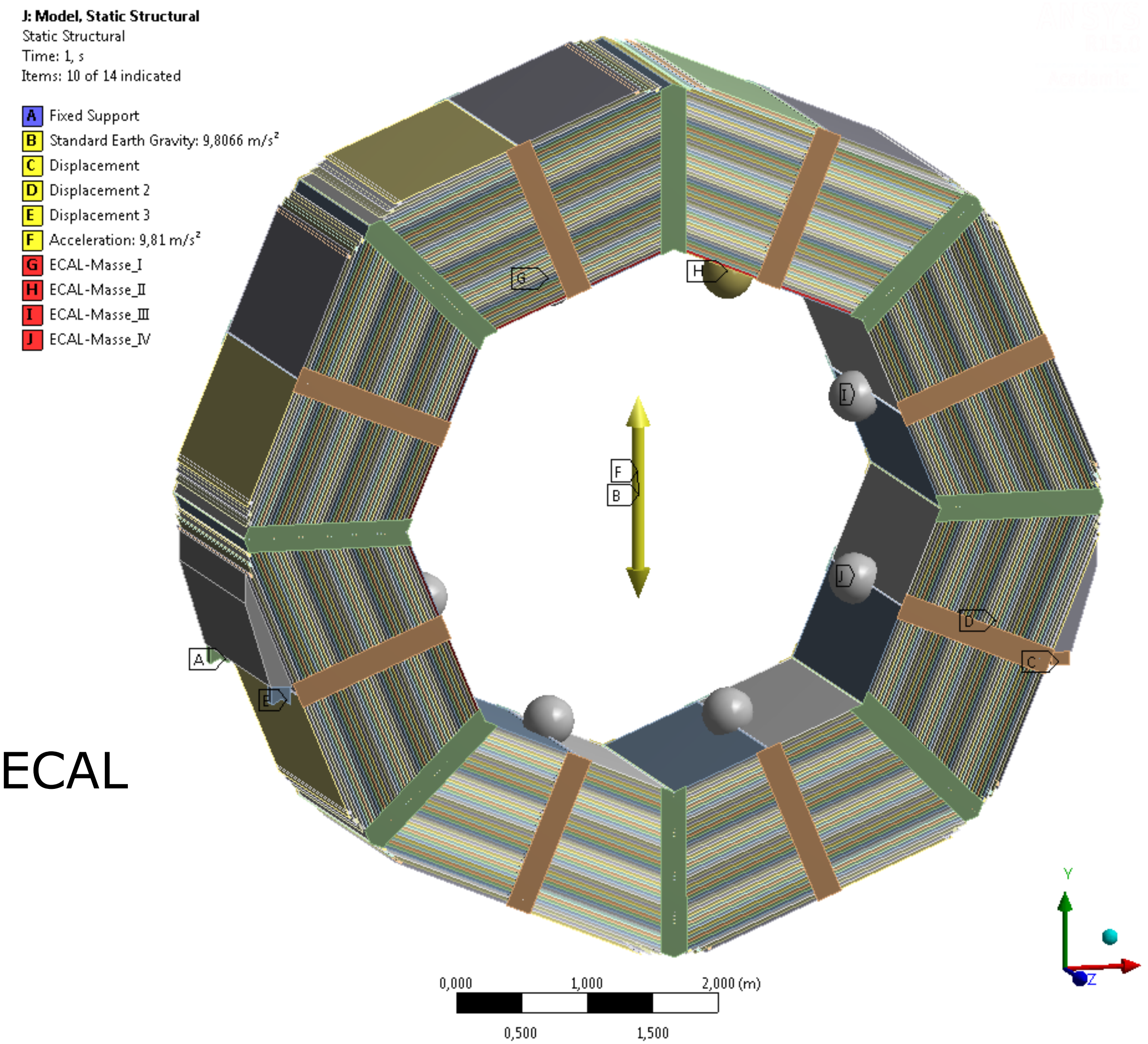






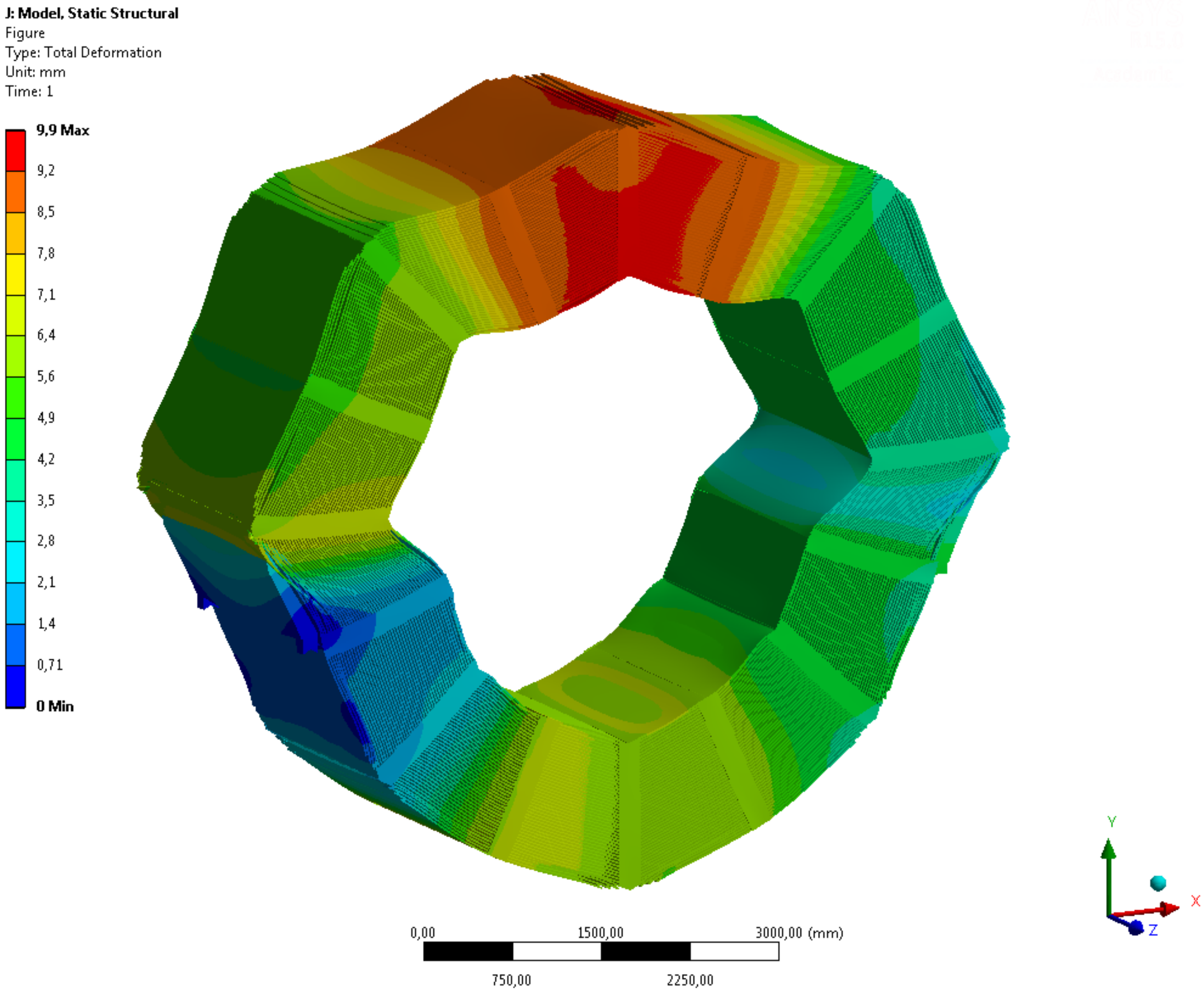
- need some modification of module connection pates

Ring structure



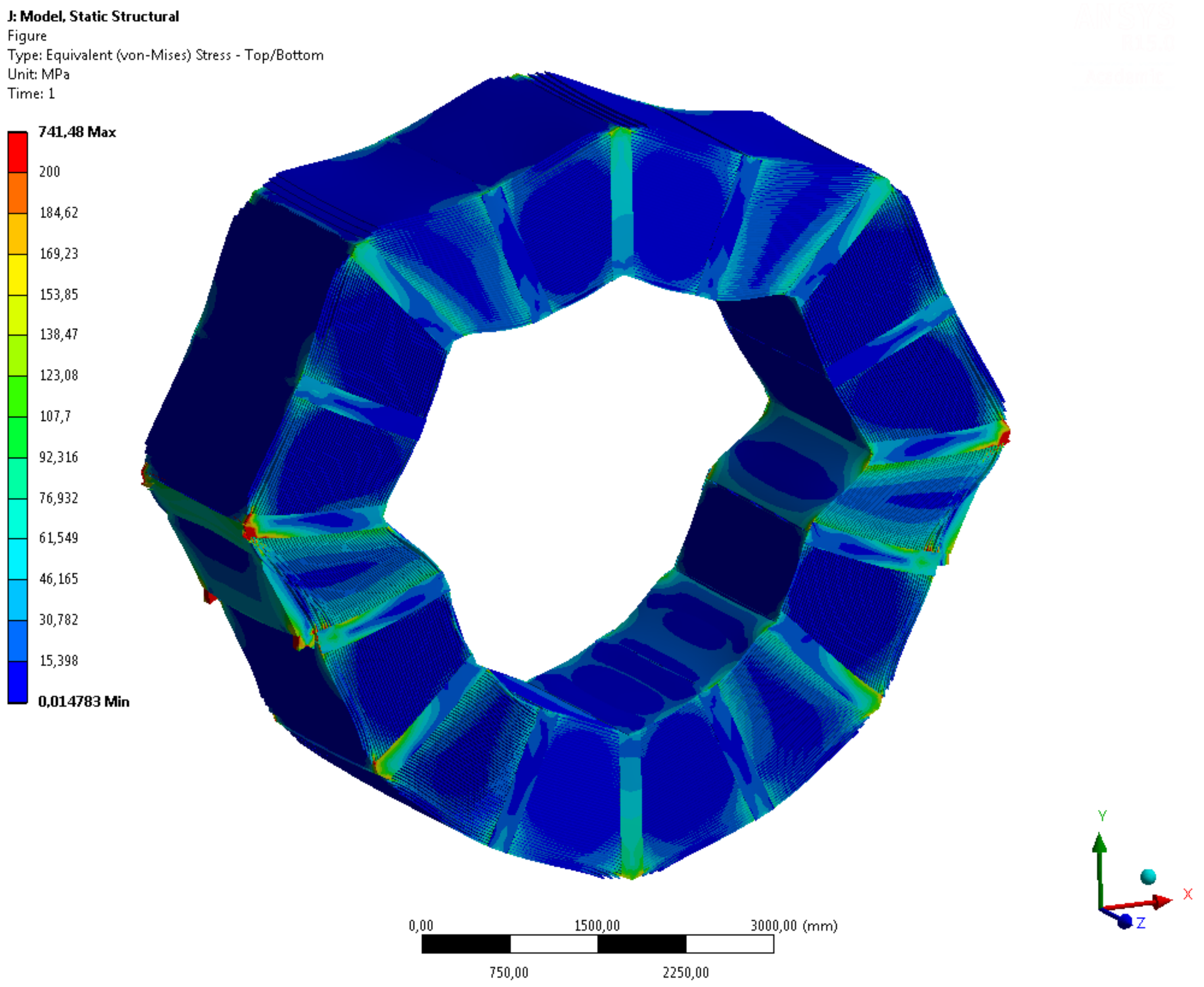
- model includes ECAL masses

Ring deformation



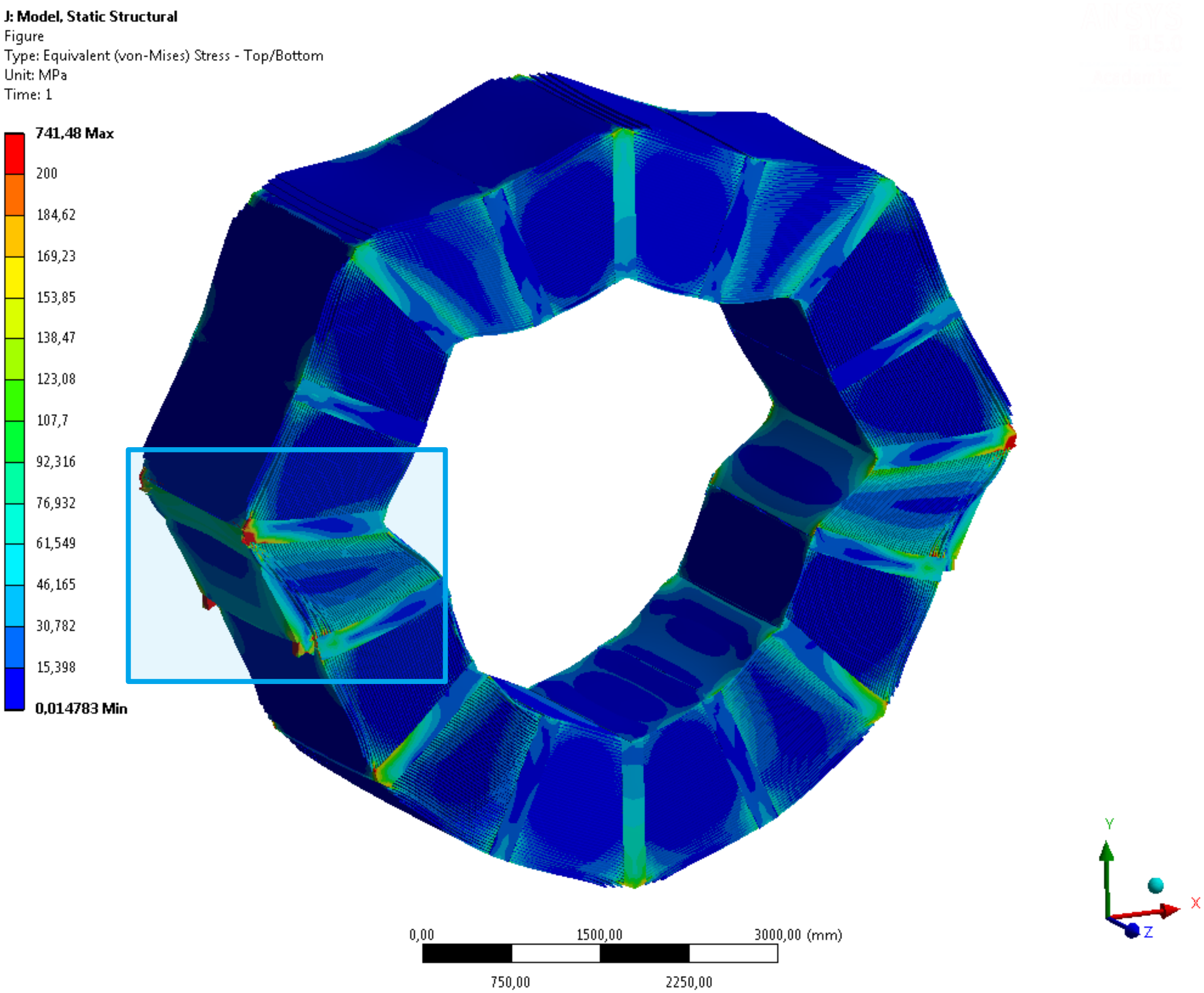
- max 10 mm

Local stress peaks



- max tension 360 N/mm^2 - safe

Local stress peaks



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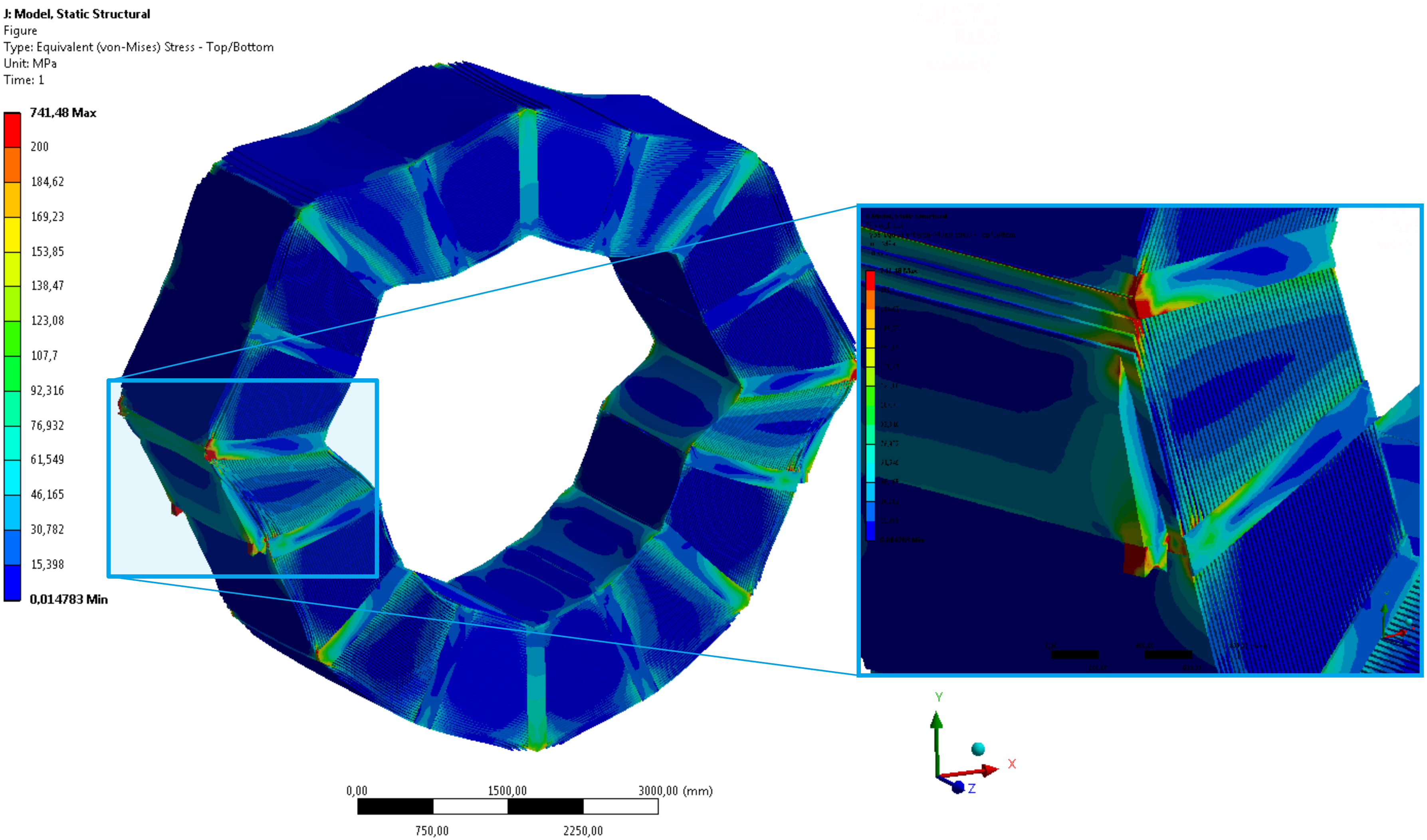
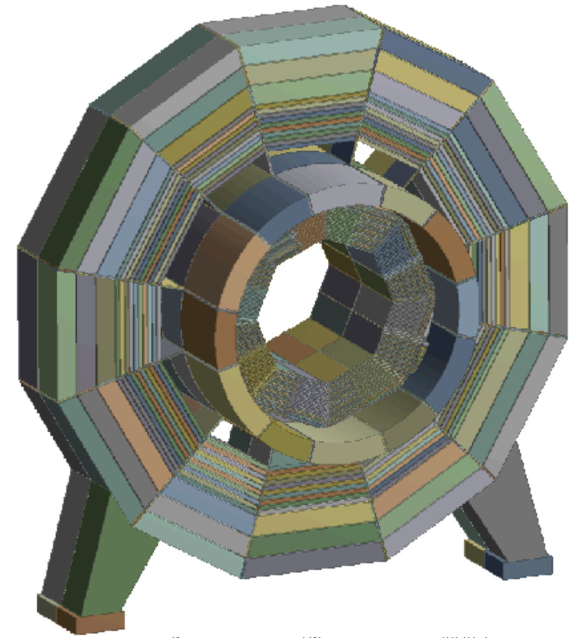


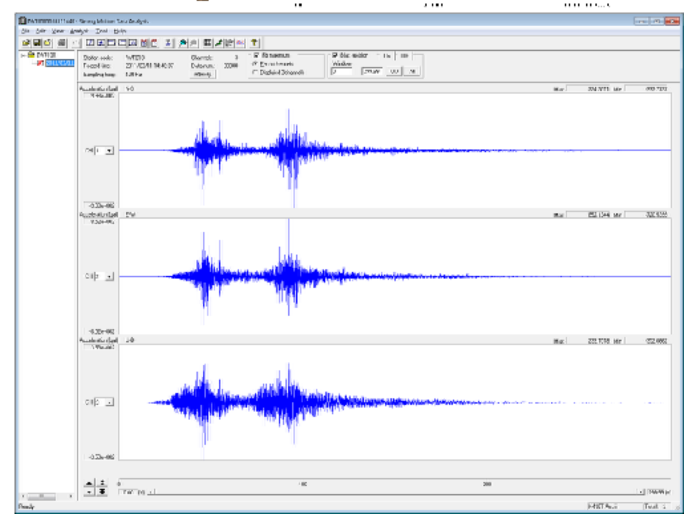
- max tension 360 N/mm^2 - safe

Dynamical stability

Dynamic analysis

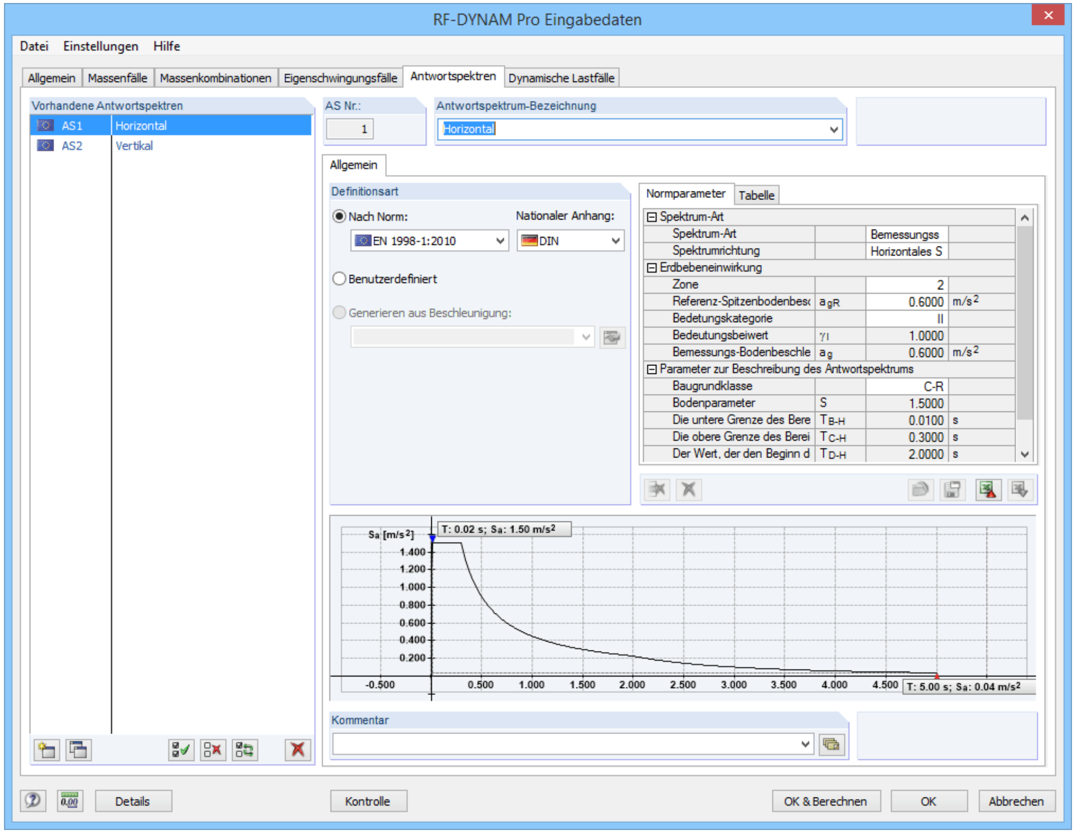
- In principe one needs to study the entire system of yoke, cryostat and HCAL
- Not enough details known: assume rigid transmission of excitation forces to HCAL and study HCAL alone
- Steps:
  - eigen mode analysis
  - response spectrum (with damping)
  - excitation with real earth quake wave form
    - East-West 0,36 g
    - North-South: 1,02 g
    - Vertical: 0,36 g





EQ data processing

- Earthquake data from NIED (Japan) can be processed using commercial software „RSTAB“ from DLUBAL (link: https://www.dlubal.com)
- Input: measured accelerations
- Output: tabular wave form to be directly used as acceleration boundary conditions in ANSYS
- Greatly simplifies work



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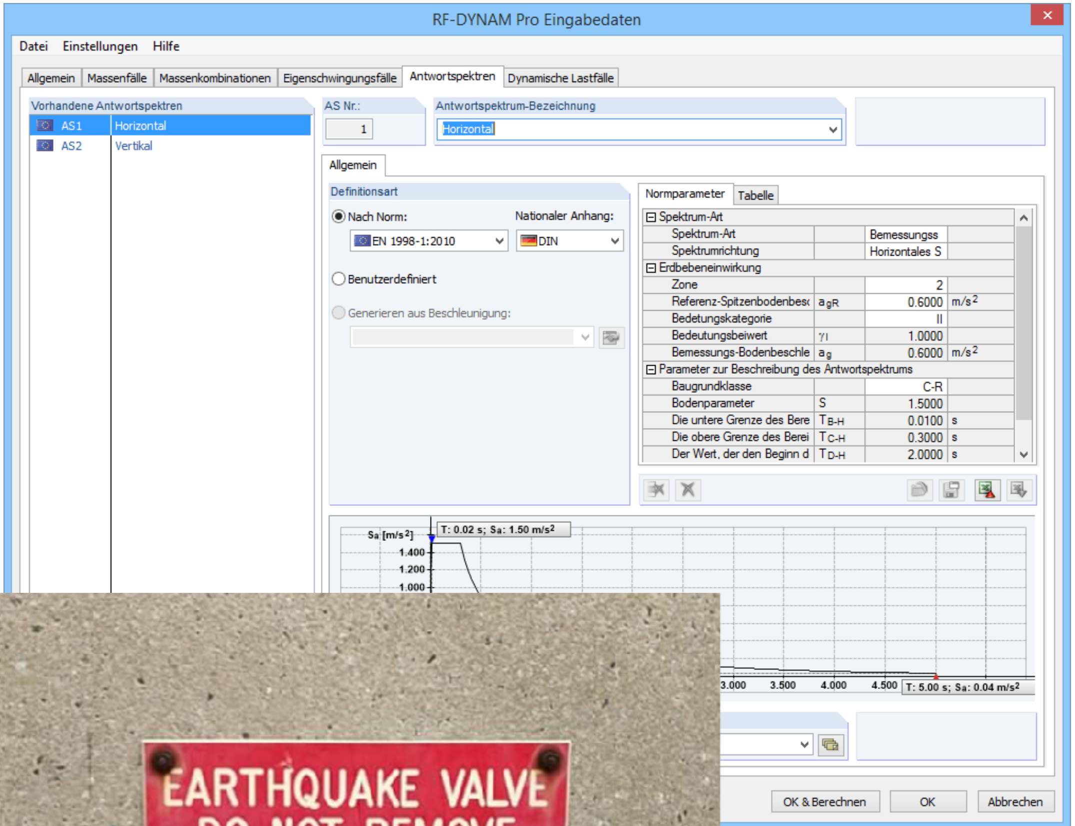
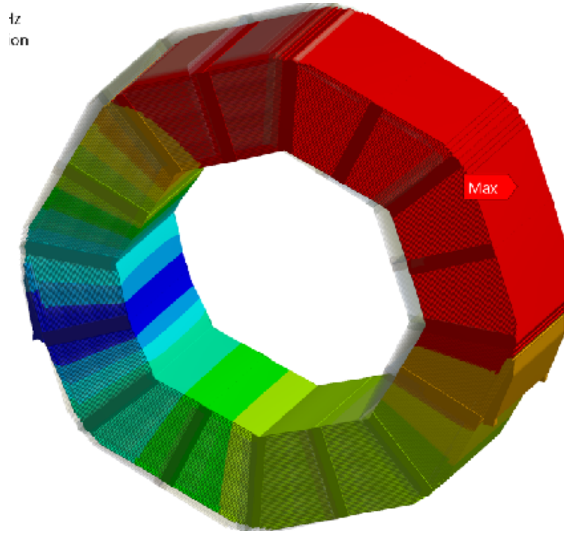
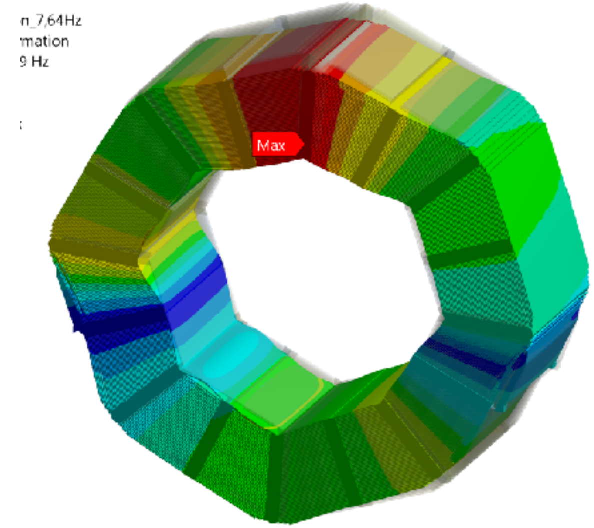
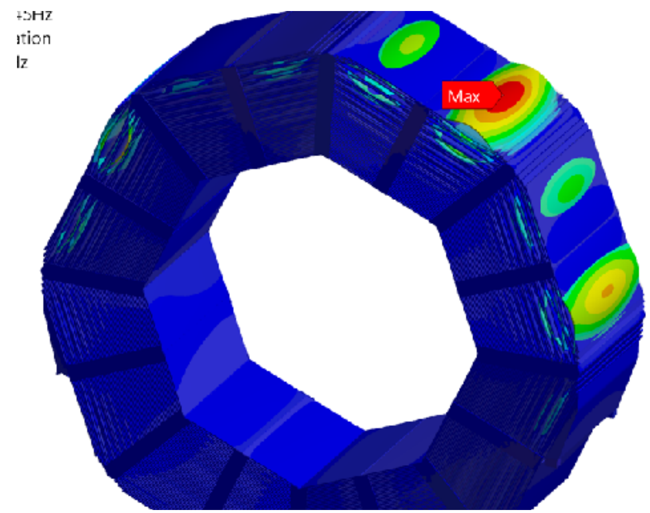


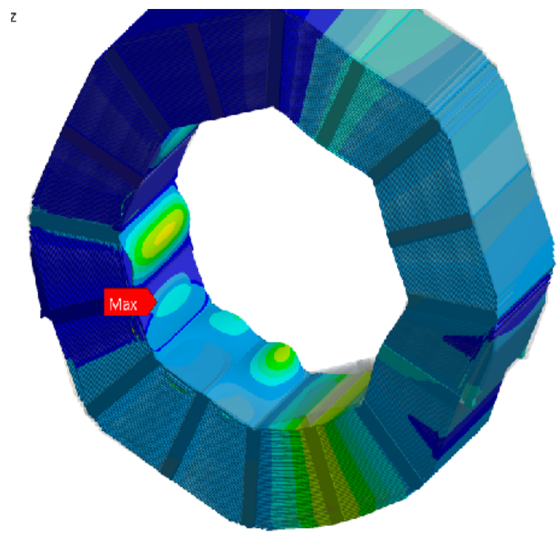
Eigen mode analysis

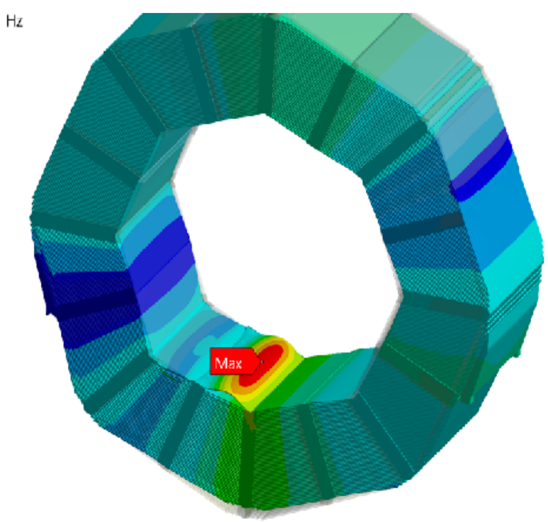
- Swinging barrel: 3Hz
- Swinging module: 8Hz
- Swinging plate: 6Hz
- Higher modes: 15 Hz
- Several plates: 45 Hz











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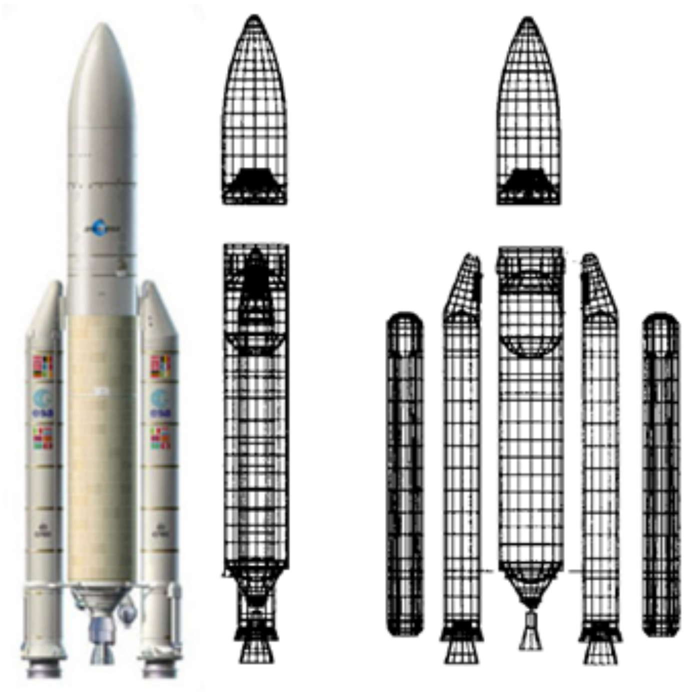
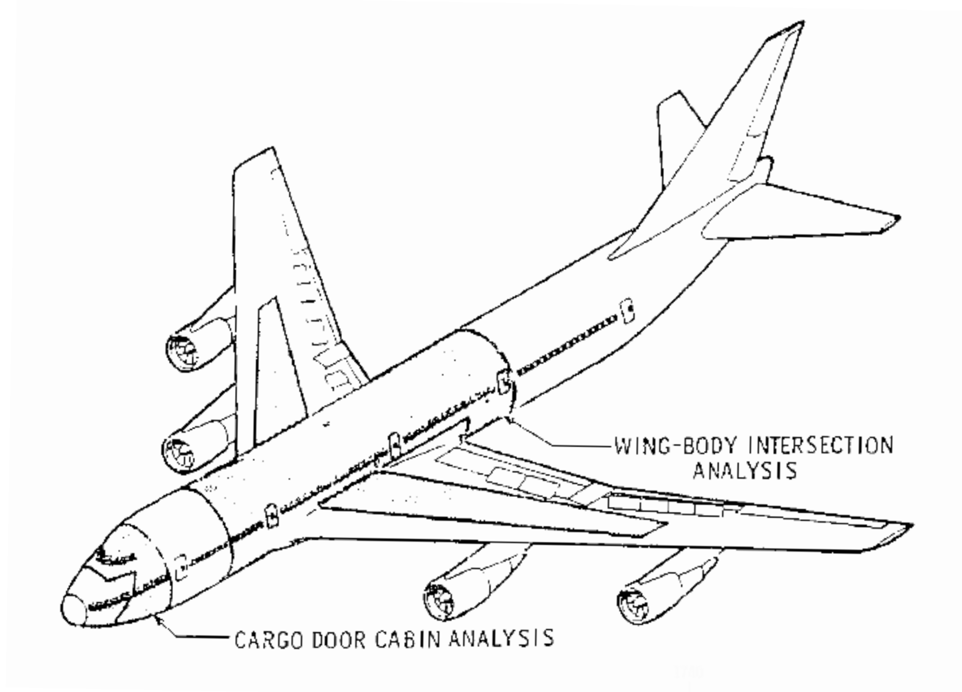
Computational challenges

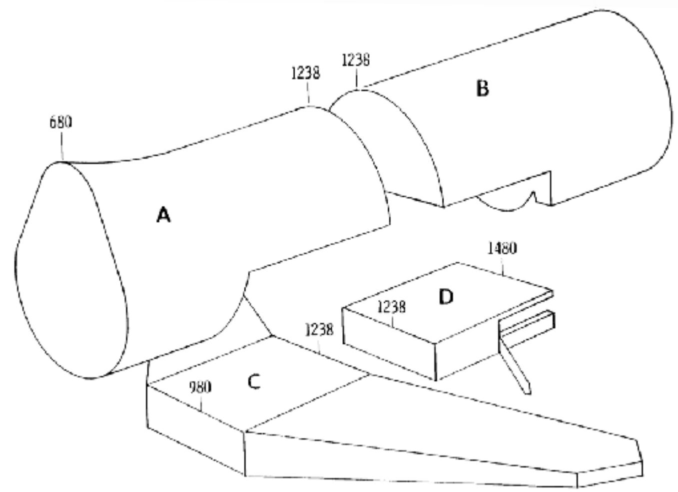
- Within reasonable effort, first 200 eigen modes calculated
- In order to obtain response spectrum with a frequency sweep, need to introduce damping: further complication
- Computation failed

- Possibilities to simplify:
  - omit details: use shells, beams, point masses, rigid bodies
    - loss of realism and predictive power
- More efficient approach: **sub-structured analysis**
  - condense group of elements into a "super-element"
  - model behaviour for the overall structure in a matrix describing the characteristic properties of the super-element
    - rigidity matrix exact, mass and damping matrix approximative

Examples

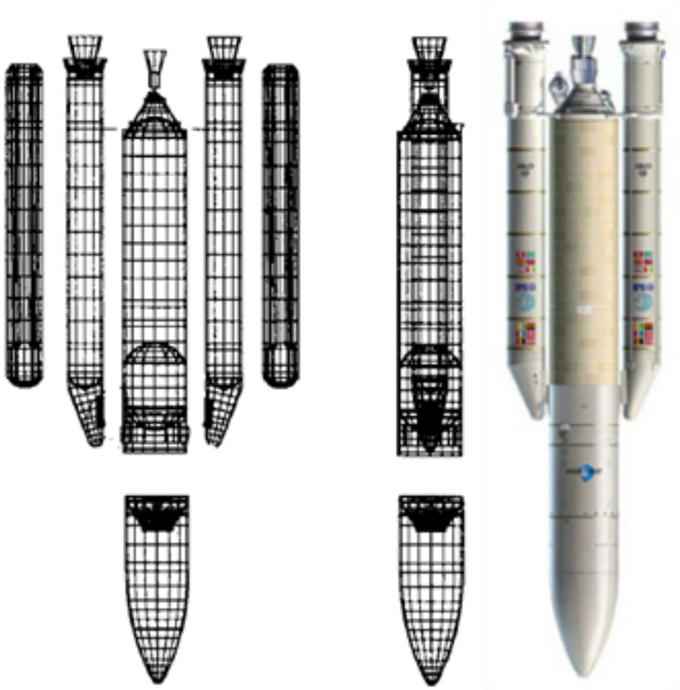


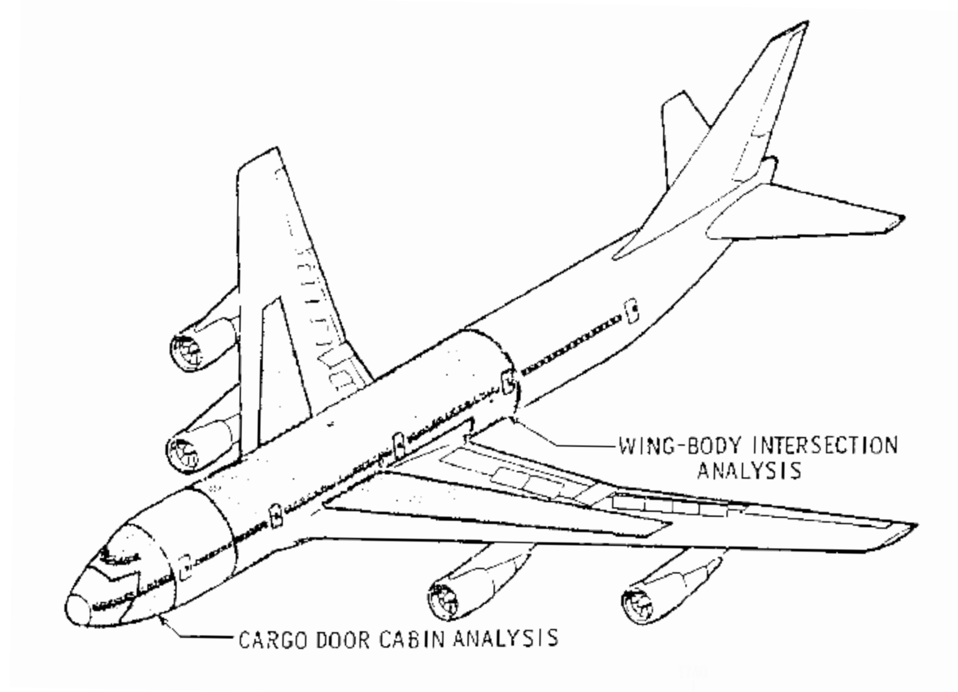




- Method commonly used in aerospace and automotive engineering since 1970s

Examples





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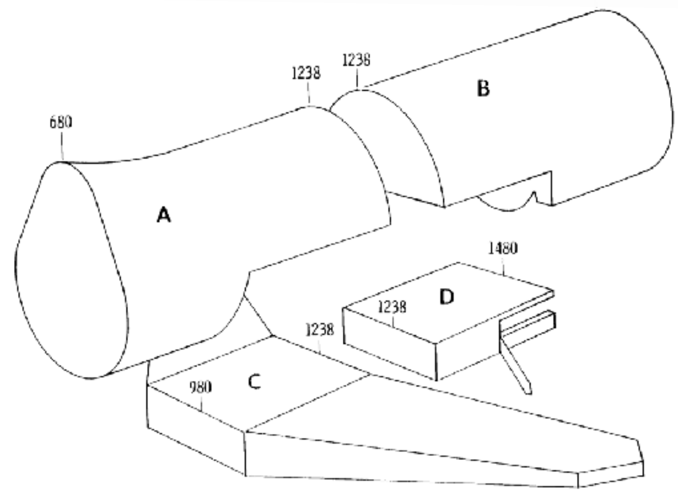
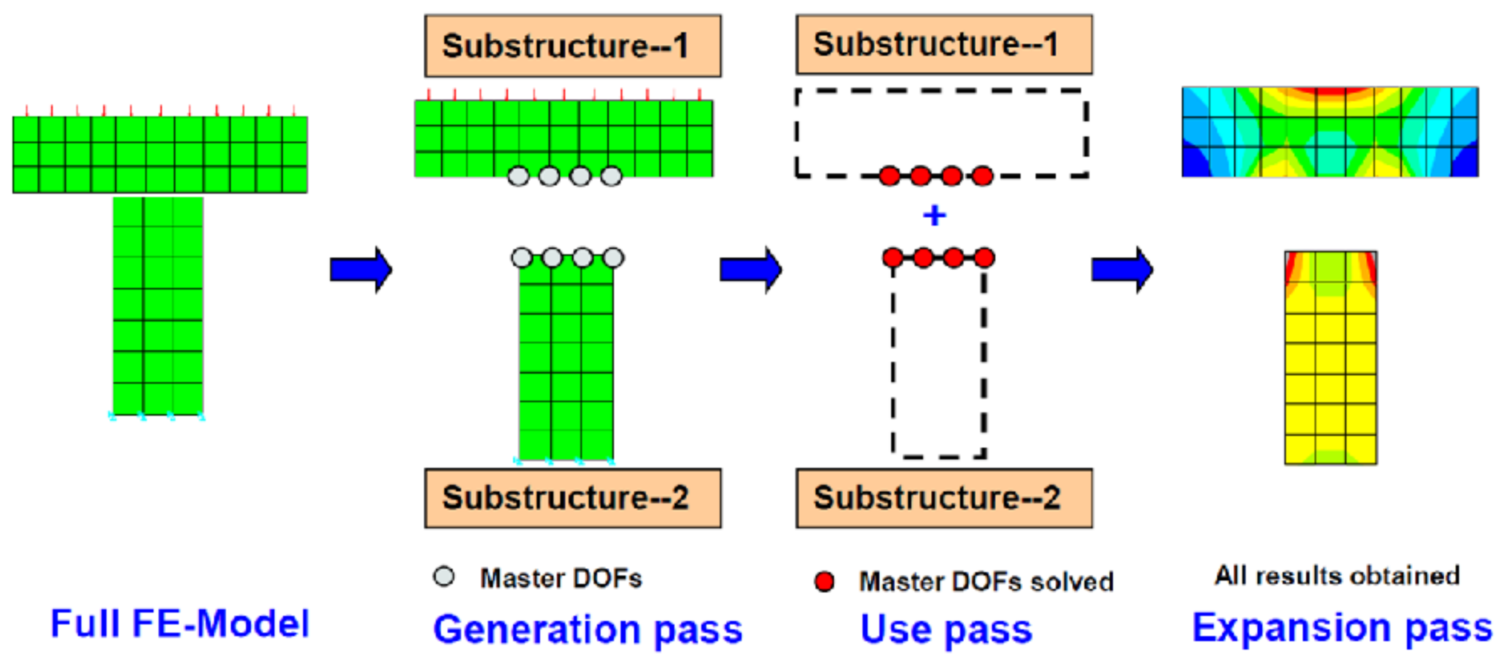


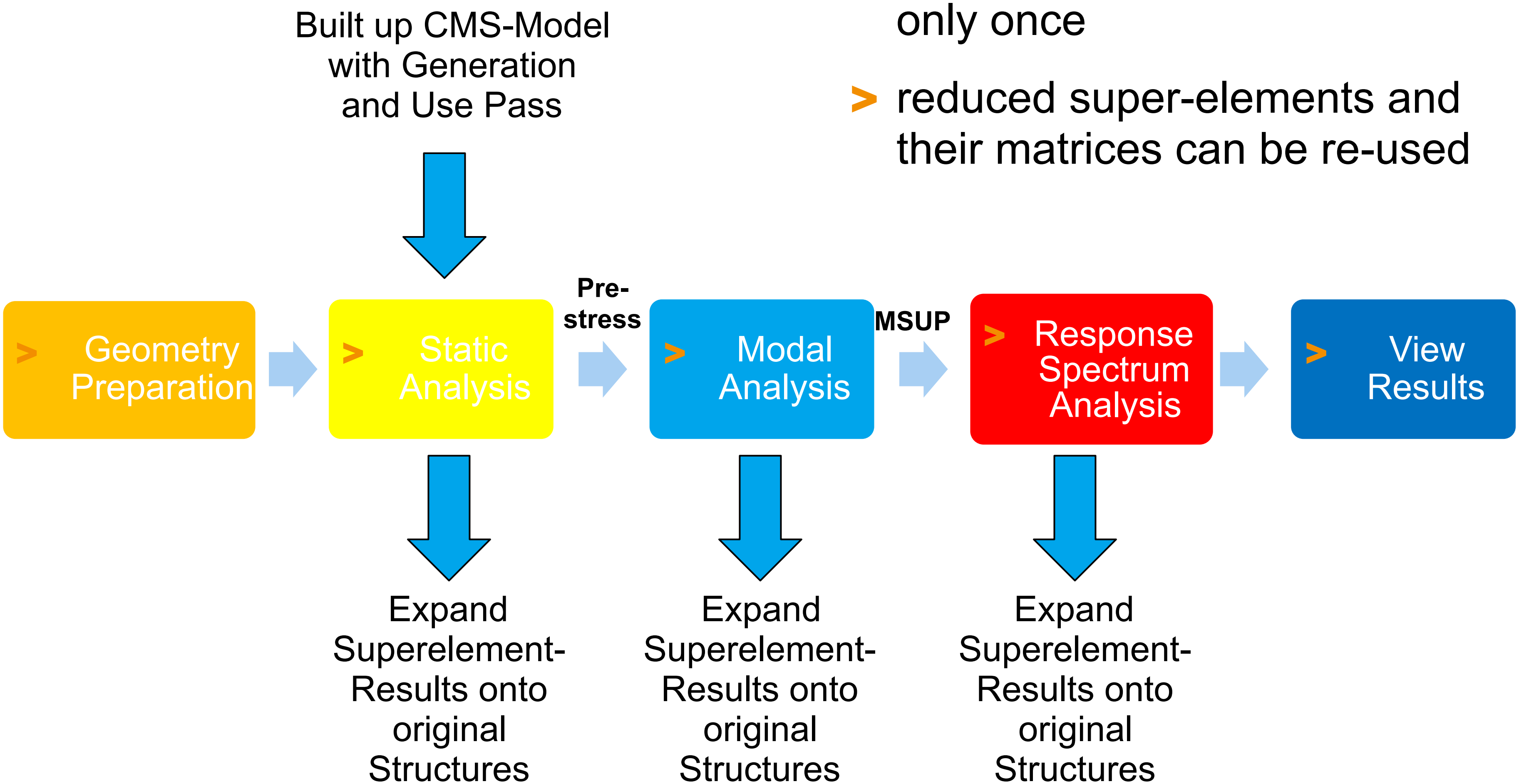
Sub-structured analysis method

- "Component mode synthesis
- Using ANSYS parametric design language APDL
- Generation pass: calculate matrices and master degrees of freedom (MDOF) at super-element boundaries
- Use pass: integrate full striche, using MDOFs
- Expansion pass: back-propagate results into super-element

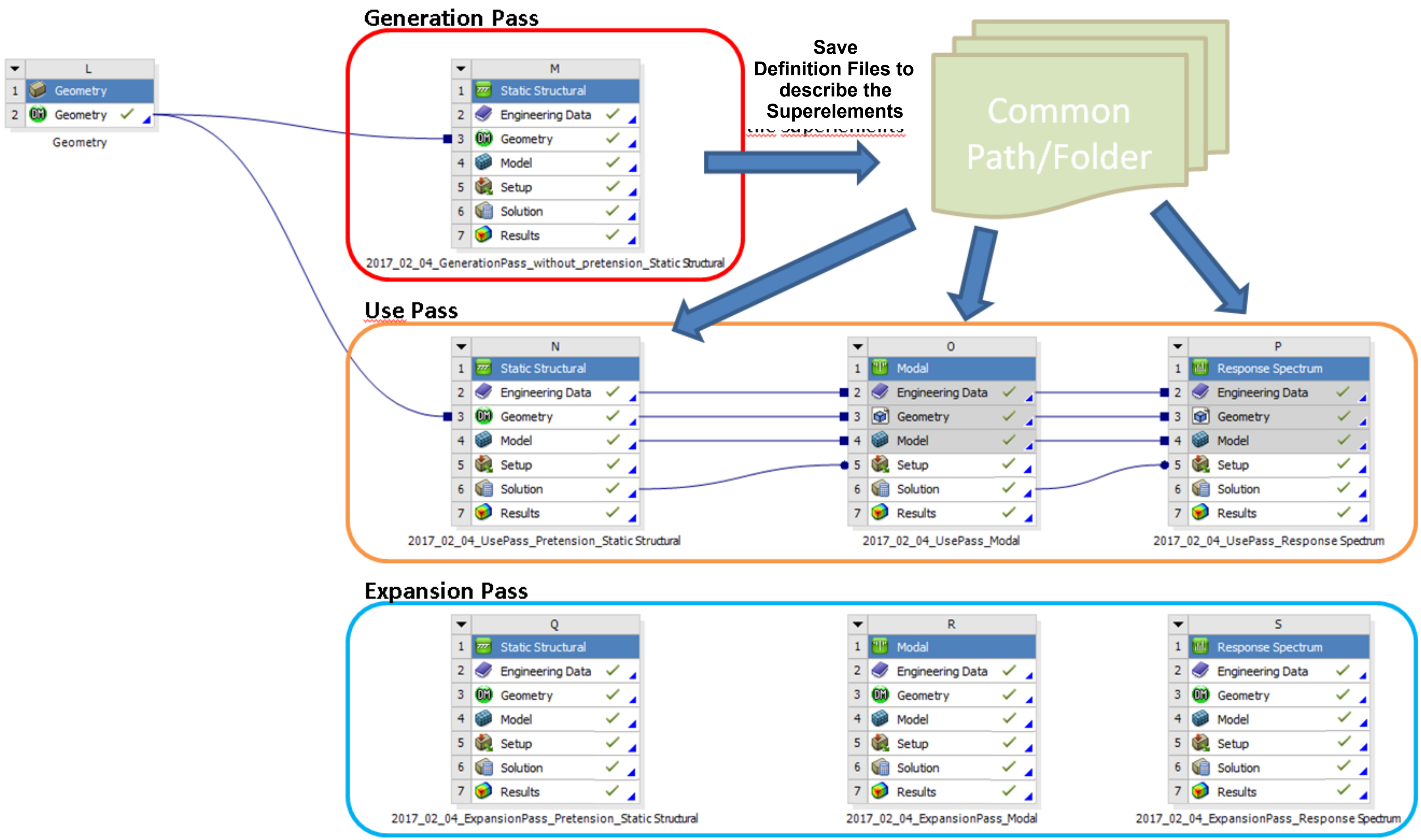


Substructuring – Implementation

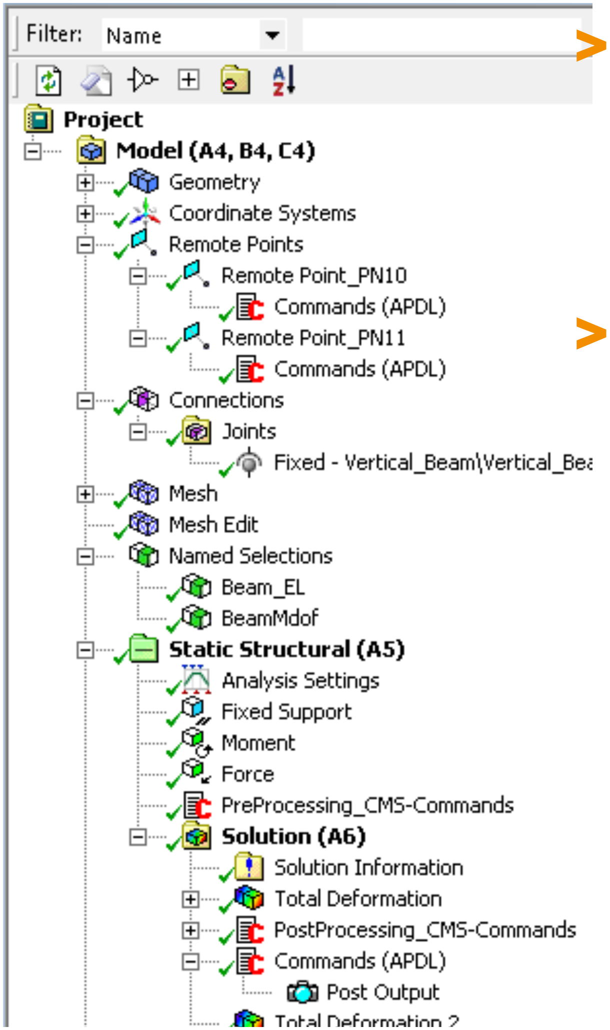
- Generation pass must be done only once
- reduced super-elements and their matrices can be re-used



Organisation of the CMS analysis within ANSYS



In practice



> Prepare geometry

- general simplifications
- find interfaces and MDOFs (few, and not in regions of high gradients)

> Build up FE model

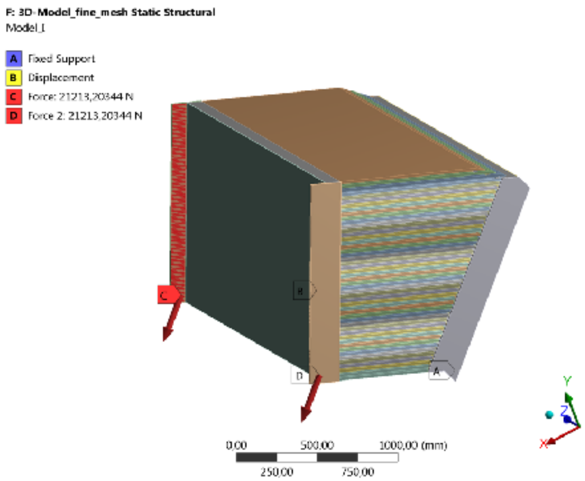
- Define local coordinate systems at boundary faces

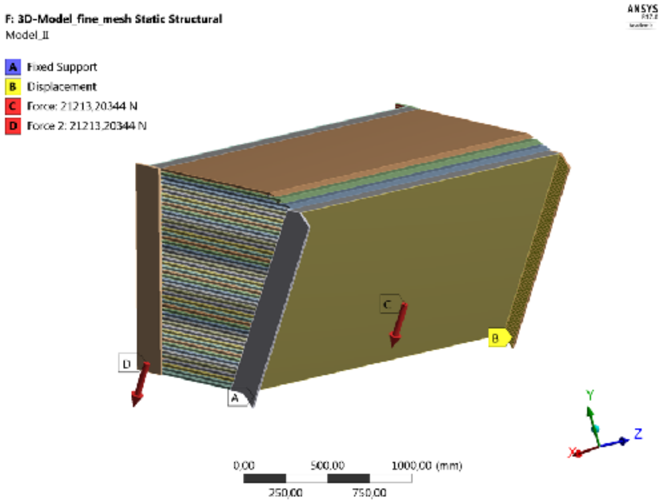
=> maintain full update capability

- Define Remote Points at the boundary surfaces to reduce number of MDOF (optimise performance)
- Model components (named selections) using ANSYS work bench and APDL
- Generation, Use und Expansion Pass within ANSYS, command objects APDL defined

Computing times– Example AHCAL structure

- Static model
- Full 3D FE-model
  - Nodes: 609.544
  - DOF: 3.657.264
- CMS FE model
  - Master-Nodes: 384
  - Master-DOF: 2.304

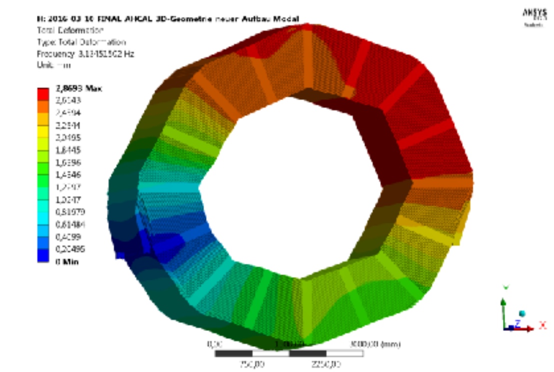


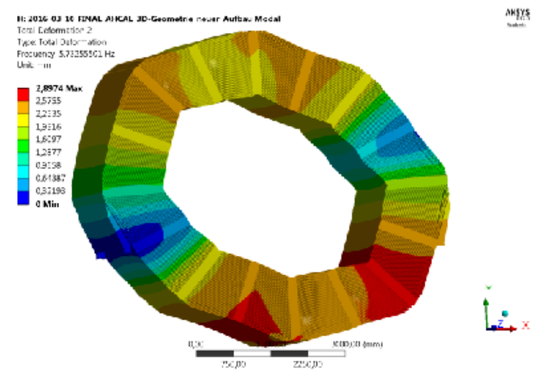


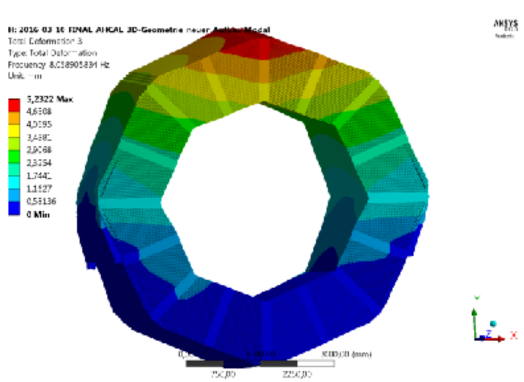
Solution Time [in sec.]	3D-Modell	CMS-Modell
Solut. Use Pass	246	25
Total Time	246	95
Total CP-Time	10.549	975

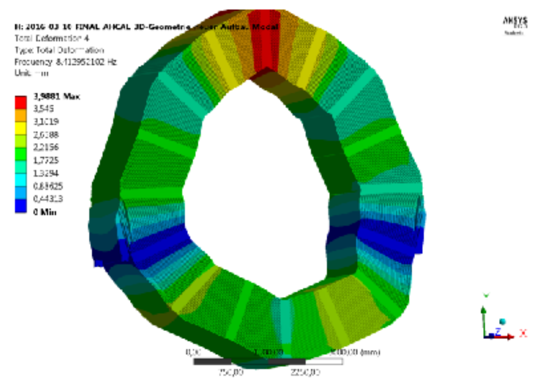
General AHCAL-Model

> Results CMS-Model:





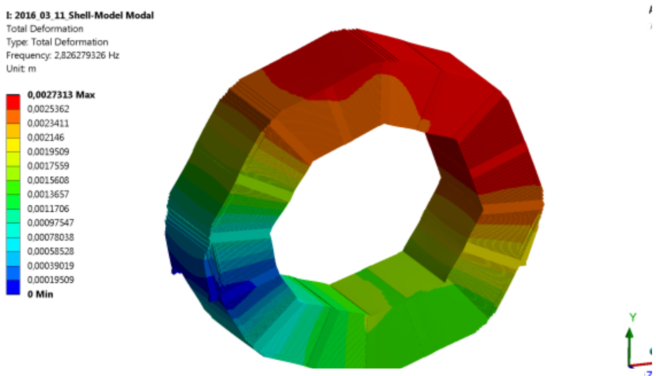


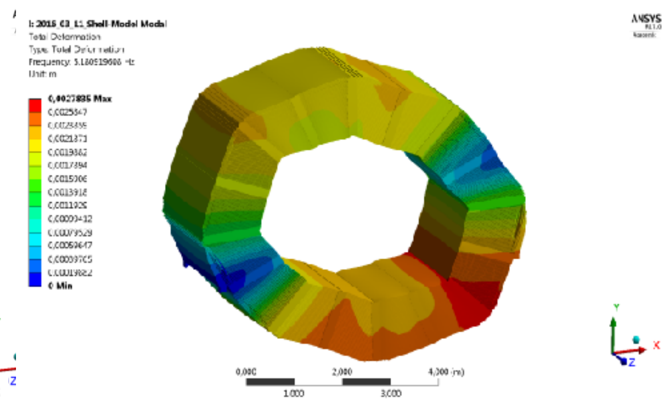


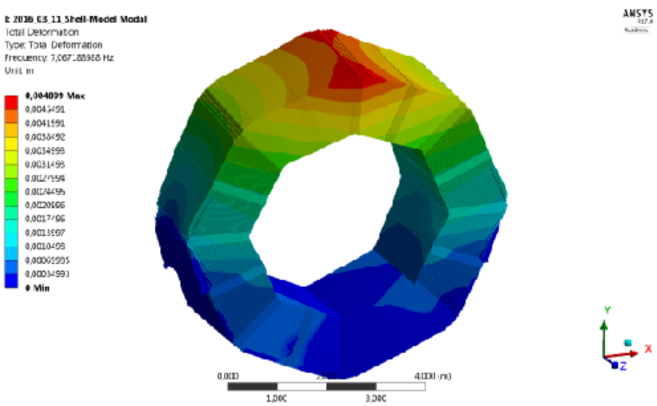
Shell-Model (prestressed)		Shell-Model (free)		CMS-Model (free)	
Nr.	f [in Hz]	Nr.	f [in Hz]	Nr.	f [in Hz]
1	2,97	1	2,83	1	3,13
2	5,27	2	5,18	2	5,73
3	6,11	3	7,07	3	8,06
4	7,65	4	7,46	4	8,41
5	9,16	5	9,94	5	10,84
6	9,85	6	11,60	6	12,91
7	11,68	7	13,65	7	15,02
8	13,32	8	14,70	8	16,47
9	14,65	9	15,37	9	16,83
10	14,67	10	17,18	10	18,07
11	15,76	11	18,75	11	20,38
12	17,37	12	19,29	12	21,14
13	18,32	13	20,21	13	22,44
14	19,37	14	21,46	14	23,34
15	20,29	15	22,48	15	24,44
16	21,99	16	23,63	16	26,12
17	22,83	17	25,52	17	27,06
18	24,05	18	31,37	18	32,28
19	24,49	19	33,39	19	38,16
20	25,23	20	35,12	20	39,50
21	31,22	21	41,07	21	41,03
22	35,29	22	42,68	22	41,03
23	38,82	23	42,68	23	41,03
24	39,76	24	42,72	24	41,03
25	40,52	25	42,72	25	41,03
26	40,55	26	42,72	26	41,03
27	41,00	27	42,72	27	41,03
28	41,27	28	42,72	28	41,04
29	42,32	29	42,81	29	41,04
30	43,78	30	43,33	30	41,04

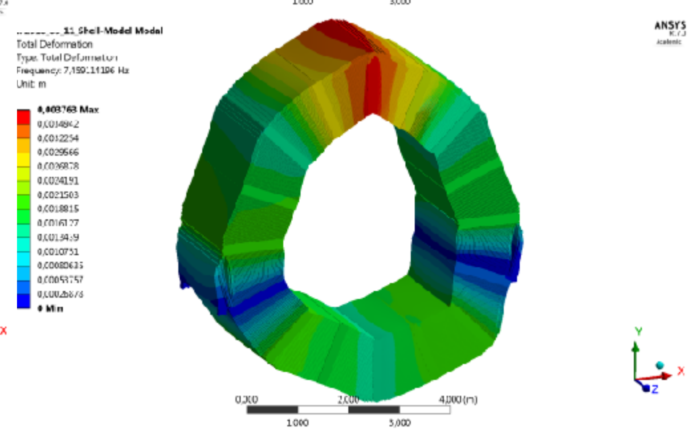
General AHCAL-Model

> Results 3D-Model:





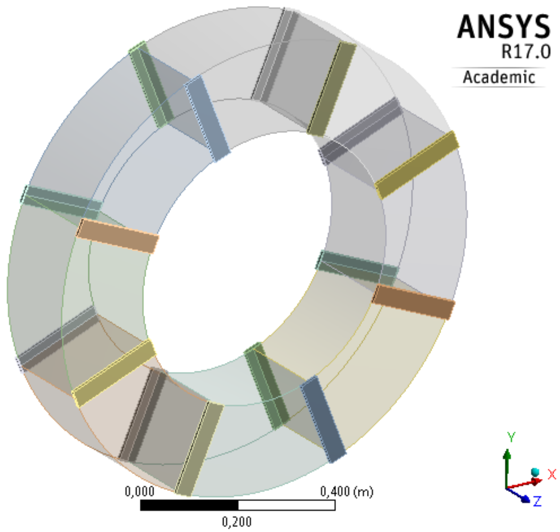




Shell-Model (prestressed)		Shell-Model (free)		CMS-Model (free)	
Nr.	f [in Hz]	Nr.	f [in Hz]	Nr.	f [in Hz]
1	2,97	1	2,83	1	3,13
2	5,27	2	5,18	2	5,73
3	6,11	3	7,07	3	8,06
4	7,65	4	7,46	4	8,41
5	9,16	5	9,94	5	10,84
6	9,85	6	11,60	6	12,91
7	11,68	7	13,65	7	15,02
8	13,32	8	14,70	8	16,47
9	14,65	9	15,37	9	16,83
10	14,67	10	17,18	10	18,07
11	15,76	11	18,75	11	20,38
12	17,37	12	19,29	12	21,14
13	18,32	13	20,21	13	22,44
14	19,37	14	21,46	14	23,34
15	20,29	15	22,48	15	24,44
16	21,99	16	23,63	16	26,12
17	22,83	17	25,52	17	27,06
18	24,05	18	31,37	18	32,28
19	24,49	19	33,39	19	38,16
20	25,23	20	35,12	20	39,50
21	31,22	21	41,07	21	41,03
22	35,29	22	42,68	22	41,03
23	38,82	23	42,68	23	41,03
24	39,76	24	42,72	24	41,03
25	40,52	25	42,72	25	41,03
26	40,55	26	42,72	26	41,03
27	41,00	27	42,72	27	41,03
28	41,27	28	42,72	28	41,04
29	42,32	29	42,81	29	41,04
30	43,78	30	43,33	30	41,04

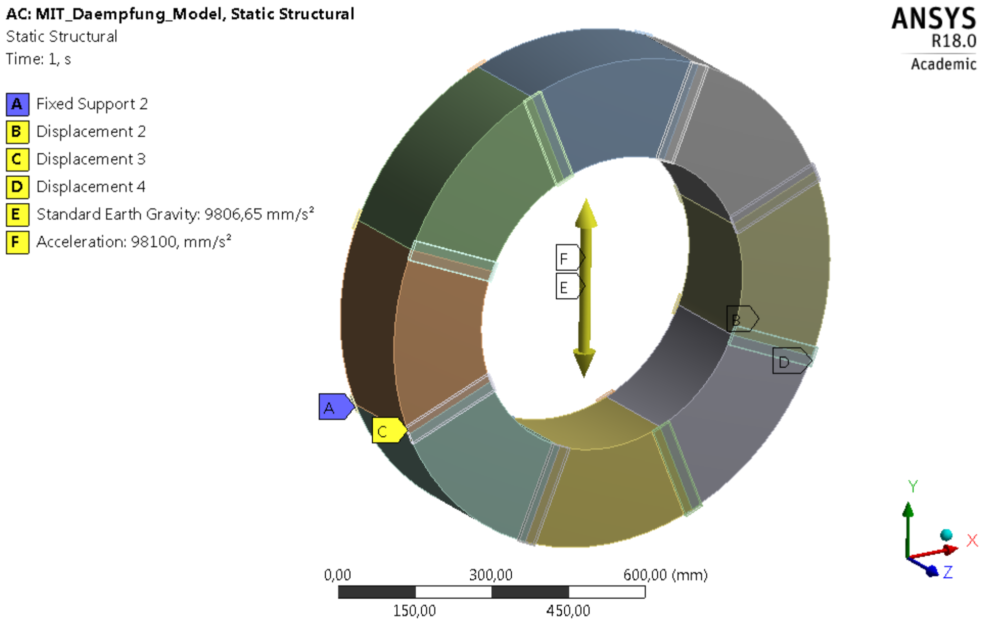
Status

- Status 4/2016: validated against full shell model for deformations and eigen-modes
- Resumed fall 2016. following parental leave of key engineer
  - Common project with DESY central mechanics service
  - Progress is slow (< 0.2 FTE)
- Go one step back and establish method with a simpler wheel-type toy model first
- Code and data handling have been re-organised
- Study dependence of computational effort on details of model
  - mesh granularity
  - number of nodes to model the behaviour at sub-structure boundaries
  - in parallel, monitor deformation results and optimise properties of nodes
- Collected lots of experience
  - need to invest in efficient and intelligent boundary modelling in order to save computing effort
- Full analysis chain for toy model appeared in reach for this meeting
- Hope to return to full HCAL structure soon



Test model: ring structure with 8 sectors

- At small scales, represent problem, including several segments, contacts between segments via connection plates, and overall ring shape
- Support analogue to complete AHCAL model, but additional ECAL masses not included
- Can easily be adapted for different investigations
- The full pass through the analysis can in principle be transferred to the AHCAL FE model



Studies with the test structure

- Static analysis to obtain pre-tension under gravity
- Transfer results from the static analysis to the FE model for subsequent modal analysis to obtain eigen-modes and frequencies
- Transfer results from the modal analysis to the dynamic analysis
  - use modal super-position to obtain response of the structure to excitation spectrum
- Present results as Bode plots
  - amplitude and phase shift as a function of frequency

Result data management

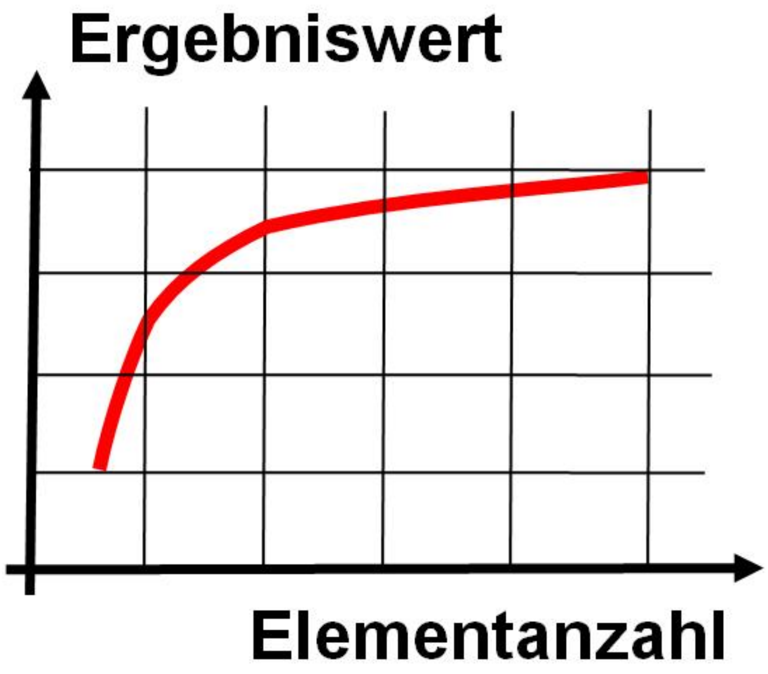
- in past analyses we had problems with huge result files (for Modal Analysis up to 400 GB)
- one part of the problem is the number of Master DOF in an analysis
- a second part is the type of result data, which is needed to do an appropriate pst processing of dynamic FE-Models
- a simple test model show the influence on requested result type in the analysis set up
- the following table shows different result file sizes of the test model

	Only Displacement	Nodal Forces on boundary conditions	All Nodal Forces
Static	9 MB	36 MB (+300%)	42 MB (+366.7%)
Modal	6 MB	23 MB (+283.3%)	40 MB (+ 66.7%)
Harmonic	213 MB	872 MB (+309.4%)	1 GB (+ 369.5%)

- **Lessons learnt:**
- **As soon as results on stresses - even if only in parts of the model - are added, data volume increases drastically**
- **Next to the number of master nodes, biggest driver of data volumes for complex analyses**
- **Conclusion: first, go for displacement only, then obtain stresses in critical areas**

Mesh convergence

- For final calculations use only mesh set-up which have been validated on a model with a single segment
- Verify that results do not change for even fier cell sizes
- Systematic study using different model types, cell sizes and numbers of MDOF

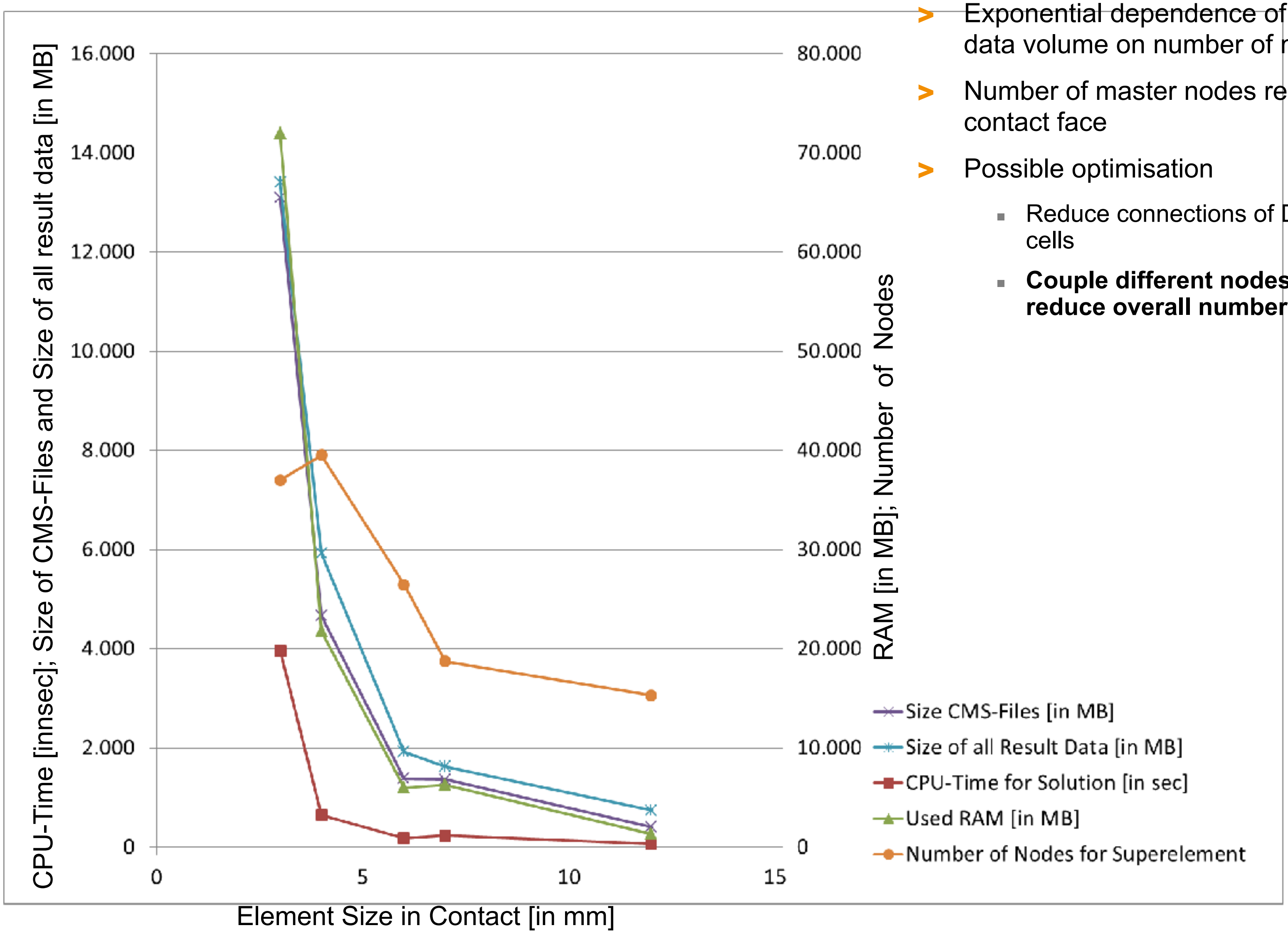


Study on model variants and resulting file sizes for result data

- Reference: calculation with full 3D structure
- If only one node with coupling to remote point is used on contact surface, CPU time does not depend on number of elements at contact face
  - accuracy invariant, ~3%
- If several master nodes are used, but without coupling to remote point, better accuracy, ~0.7%
- Conclusion: use 3 master nodes per contact face

Analysen-Uebersicht									Bei allen Analysen in den Ergebnissdaten nur Verformungen gespeichert !!!												
lfd. Nr.	Was?	Bemerkung	Analyse-Art	CMS (j/n)	Mesh-Elements	Mesh-Nodes	Element size on Contact face [in mm]	Gesamt-verformung [in mm]	Verformung im Vergl. Zur Referenz-rechnung [in 100%]	Solution-CPU-time [in sec]	Total-CPU-time [in sec]	Used RAM [in MB]	Allocated RAM [in MB]	CP-Rate [in Mflops]	Size Super-element [in MB]	data size segments [in MB]	total data size [in MB]	Anteil Data Size CMS an Gesamt [in %]	large defor-mations	Damping	Solver
1	**Referenzrechnung 3D**	**Referenzmodell 3D**	Stat.-Mechan.	n	202.960,00	1.117.692,00	4,50	**2.409,70**	100,00	311,30	598,30	31.135,00	32.405,00	44.541,90	0,00	0,00	2.657,14	0,00	off	no	PCG
2	**Testrechnung 3D**	**coarse global mesh density**	Stat.-Mechan.	n	6.006,00	13.062,00	32,00	2.175,90	90,30	2,90	9,70	172,00	2.112,00	6.102,60	0,00	0,00	43,60	0,00	off	no	Sparse, direkt
3	**Testrechnung 3D**	**medium global mesh density**	Stat.-Mechan.	n	10.959,00	34.529,00	32,00	2.297,00	95,32	5,60	14,60	510,00	2.112,00	13.818,40	0,00	0,00	92,20	0,00	off	no	Sparse, direkt
4	**Testrechnung 3D**	**fine global mesh density**	Stat.-Mechan.	n	36.207,00	64.709,00	22,50	2.344,60	97,30	11,60	26,20	954,00	2.112,00	18.582,30	0,00	0,00	216,00	0,00	off	no	Sparse, direkt
5	**Testrechnung mit einem SE mit RP und Joints**	**coarse global mesh density**	Stat.-Mechan.	j	7.471,00	16.251,00	45,00	2.329,70	96,68	16,40	38,30	489,00	2.112,00	1.928,80	0,26	194,00	246,00	78,86	off	no	Sparse, direkt
6	**Testrechnung mit einem SE mit RP und Joints**	**medium global mesh density**	Stat.-Mechan.	j	10.959,00	34.529,00	32,00	2.350,70	97,55	25,00	59,80	604,00	2.112,00	1.808,50	0,32	231,00	399,00	57,89	off	no	Sparse, direkt
7	**Testrechnung mit einem SE mit RP und Joints**	**fine global mesh density**	Stat.-Mechan.	j	36.207,00	64.709,00	22,50	2.392,60	99,29	69,50	113,00	2.166,00	4.143,00	3.095,40	0,58	975,00	1.149,00	84,86	off	no	Sparse, direkt
8	**Testrechnung mit einem SE mit RP und Joints**	**coarse global mesh and small number of MDOF**	Stat.-Mechan.	j	7.975,00	17.239,00	15,00	2.331,70	96,76	17,40	39,20	540,00	2.112,00	2.219,50	0,26	211,00	265,00	79,62	off	no	Sparse, direkt
9	**Testrechnung mit einem SE mit RP und Joints**	**coarse global mesh and high number of MDOF**	Stat.-Mechan.	j	10.487,00	22.202,00	6,00	2.335,10	96,90	21,70	46,64	1.082,00	3.122,00	3.264,60	0,32	352,00	418,00	84,21	off	no	Sparse, direkt
10	**Testrechnung mit einem SE mit RP und Joints**	**coarse global mesh and very high number of MDOF**	Stat.-Mechan.	j	15.241,00	30.410,00	4,00	2.334,70	96,89	46,30	82,80	2.277,00	4.320,00	3.892,10	0,32	672,00	759,00	88,54	off	no	Sparse, direkt

Results for different numbers of MDOF



- Exponential dependence of CPU time and data volume on number of master nodes
- Number of master nodes relates to cell size at contact face
- Possible optimisation
  - Reduce connections of DOF with surface cells
  - **Couple different nodes to a pilot node, to reduce overall number**

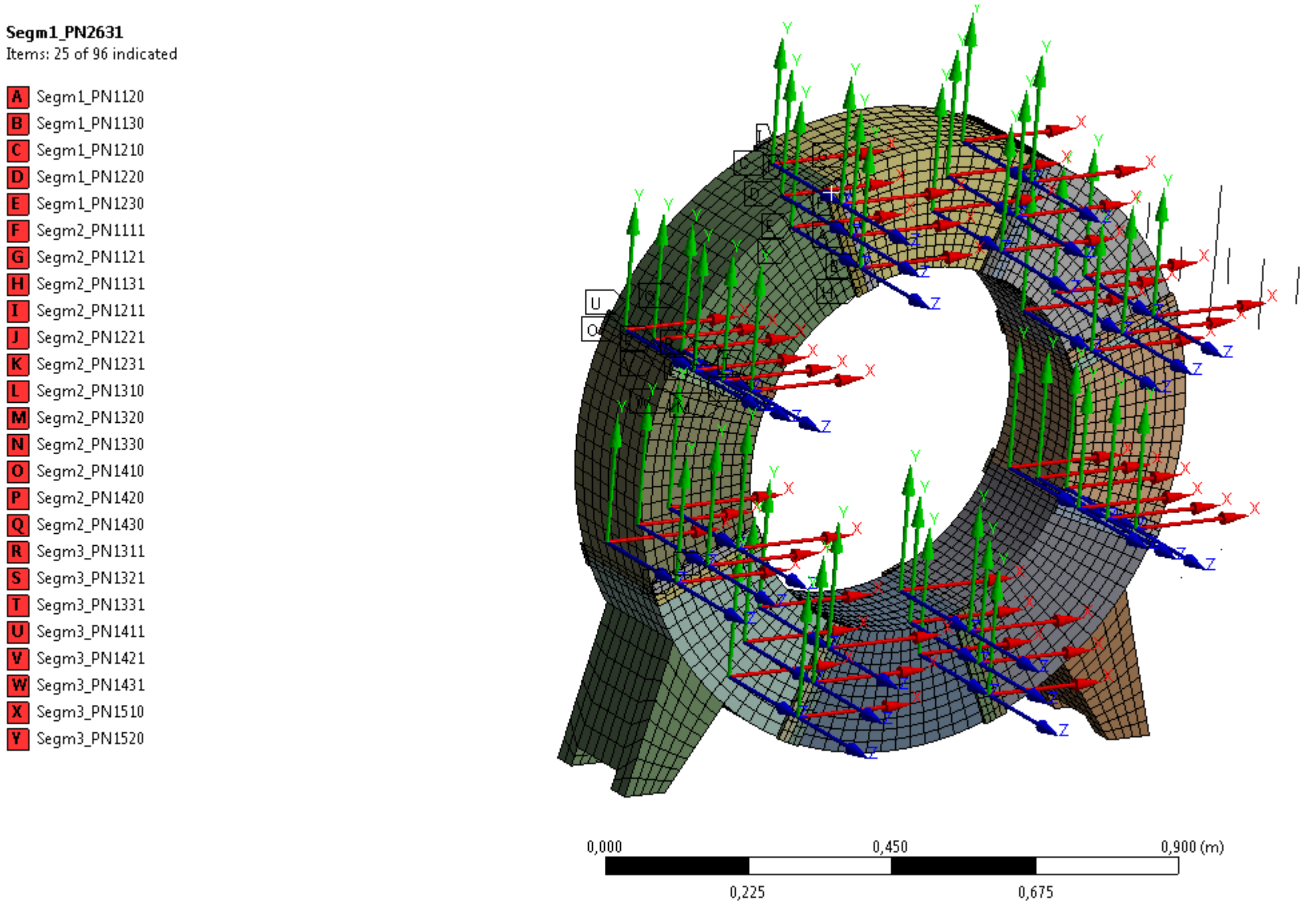
Modelling techniques

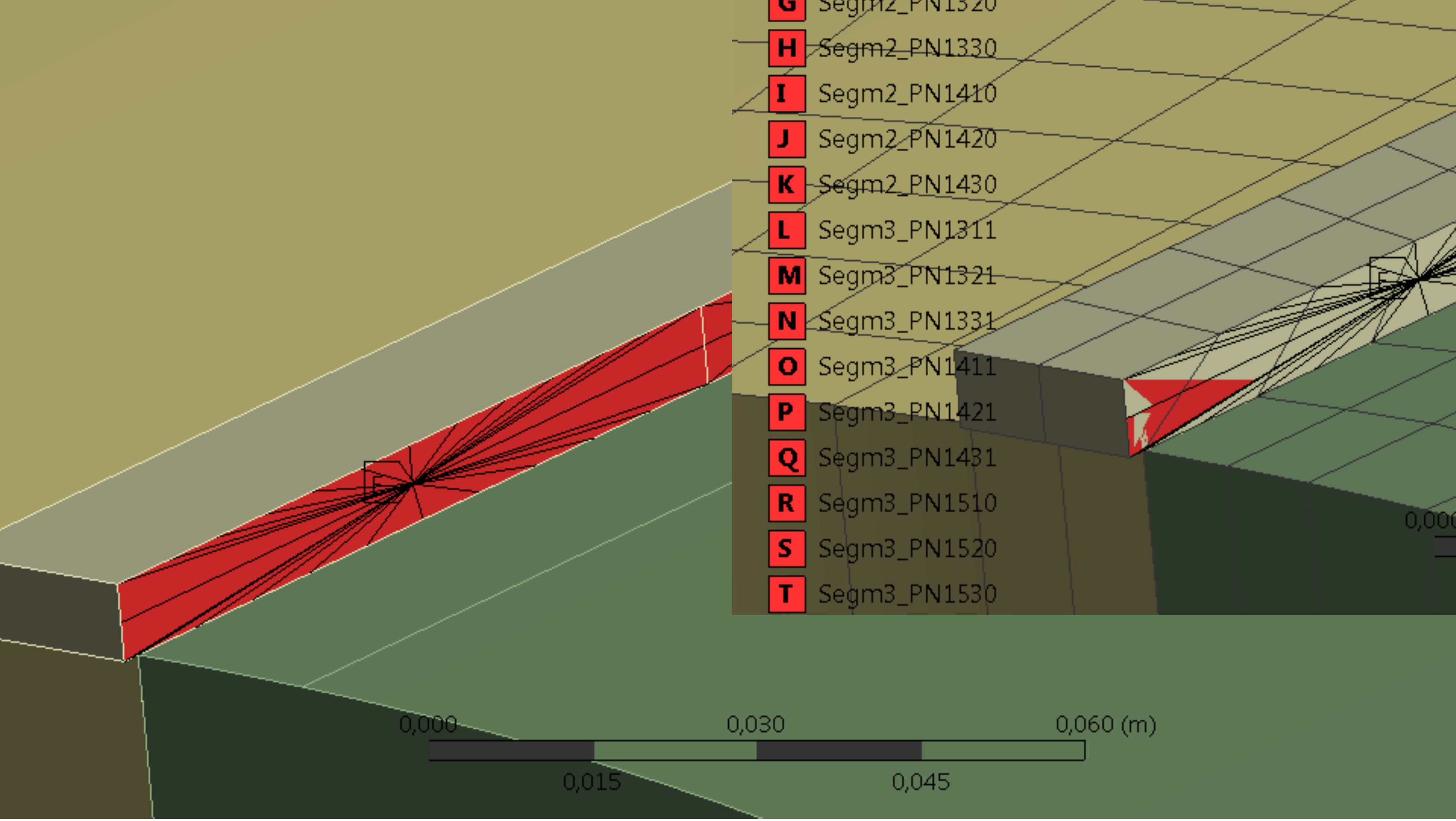
- in a previous study it is shown, that the number of defined Master DOF has a significant influence in model size and solution times
- Nodes-Coupling of common face with the use of ANSYS-Workbench features:
  - user defined coordinate systems for each face, on which the nodes have to be coupled => The position of Coordinatesystems depends on the underlying geometric face. Therefore geometric changes/updates are easier to manage
  - Remote-Point Feature in ANSYS Workbench is used to couple the nodes on one common face – internally a surface to node contact is built
  - the Joint Feature (fix joint) is used to couple the adjacent remote points of two superelements – internally a MPC-Formulation is used (MPC = Multi Point Constraint)

Present status

- Results with only one node per face led to unphysical rotations around the remote points
  - use 3 nodes
- Coupling between bodes of adjacent super-elements verified
- Still problems with the assembly of the total model, so cannot store intermediate results
- Practical issues: 16 segments, 2 faces, 3 nodes: 96 points to be defined
  - must be possible to individually access these in the full model analysis

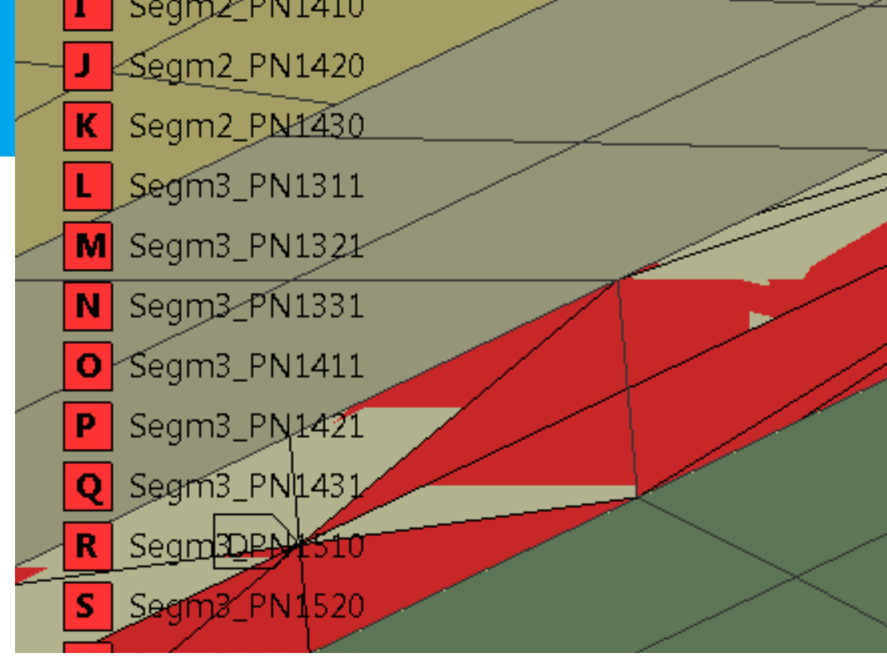
Location of remote points and their coordinate systems

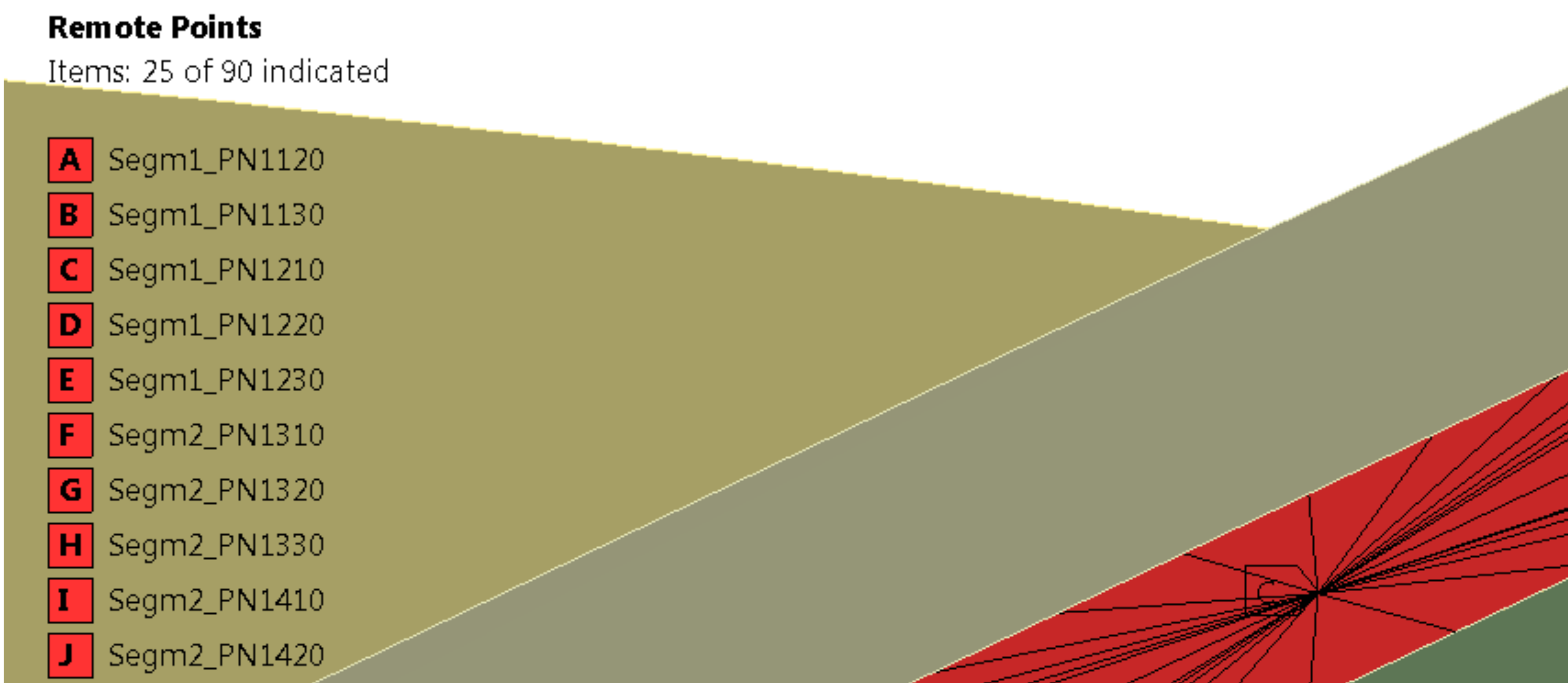




> Contact faces

In detail


J Segm2_PN1420
K Segm2_PN1430
L Segm3_PN1311
M Segm3_PN1321
N Segm3_PN1331
O Segm3_PN1411
P Segm3_PN1421
Q Segm3_PN1431
R Segm3_PN1510
S Segm3_PN1520


Remote Points
Items: 25 of 90 indicated
A Segm1_PN1120
B Segm1_PN1130
C Segm1_PN1210
D Segm1_PN1220
E Segm1_PN1230
F Segm2_PN1310
G Segm2_PN1320
H Segm2_PN1330
I Segm2_PN1410
J Segm2_PN1420

Conclusion

- Challenging project, new difficulties encountered at every step
- Circumventing computing power limitations requires brain power

- Next steps:
- Complete analysis
- Outlook:
- Validation
- use existing structures
- on a shaker

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