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BENCH-KJ: BENCHMARK ON ANALYTICAL CALCULATION OF FRACTURE MECHANICS PARAMETERS K_I AND J FOR CRACKED PIPING COMPONENTS – FINAL RESULTS AND CONCLUSIONS

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ABSTRACT

For most of design codes and for ageing consideration, fracture mechanics is needed to evaluate the integrity of cracked components. The major parameters used in this kind of analysis are K and J. In this frame, different international codes (RSE-M appendix 5.4, RCC-MRx appendix A16, R6 rule, ASME B&PV Code Section XI, API 579, VERLIFE, Russian Code…) propose compendia for stress intensity factors, and, for some of them, compendia for limit loads for usual situations, in terms of component geometry, type of defect and loading conditions.
The benchmark « bench-KJ », proposed in the frame of the OECD/IAGE Group, aims to compare these different estimation schemes regarding of in comparison to available reference results done by Finite Element Method for representative cases (pipes and elbows submitted to mechanical or/and thermal loadings, considering various type and size of cracks). Twenty-nine partners are globally involved in this benchmark, the level of their contribution depending on the considered technical task.
The benchmark covers simple cases with basic mechanical loads like pressure and bending up to complex loading combinations, but also complex geometries (pipes and elbows) including cladding or welds; all these cases are classified into 6 technical tasks: elastic stress intensity factors calculation (task 1), J calculation in cracked pipes (tasks 2 and 3), then in cracked elbows (task 4), and finally J in some particular cases (task 5) and in weld (task 6).
This paper presents the final results of the benchmark in terms of global comparison between different codes.

INTRODUCTION

For design and ageing considerations of nuclear components, fracture mechanics is needed to evaluate the component integrity in presence of a potential defect. Major parameters used in this frame are K_I and J. Different codes (RSE-M appendix 5, RCC-MRx appendix A16, R6 rule, ASME B&PV Code Section XI, API 579…) propose more or less sophisticated analytical solutions to estimate those fracture parameters. These solutions are based on compendia for the stress intensity factors and limit loads for usual situations, in terms of component geometry, type of defect and loading conditions for the J calculation. In particular, these codes propose very different ways to consider thermal loadings or cracks in a weld joints.
To have a comparative overview of the existing procedures, the benchmark named ‘bench-KJ’ has been proposed in the frame of the OECD/IAGE Group. It aims to compare these different estimation schemes by comparison to reference Finite Element solutions, for representative industrial cases (pipes and elbows, mechanical or/and thermal loadings, different type and size of cracks). The benchmark covers simple cases, with basic mechanical loads like pressure and bending, up to complex load combinations and geometries (cylinders and elbows) including cladding or welds.

A second goal of this benchmark was to propose practical applications for young engineers. 29 partners are involved in this benchmark. It has been divided into 7 tasks, with a progressive increase of the difficulty.

This paper recalls the purpose and presents the results of the different tasks of the benchmark dedicated to elastic stress intensity factor calculation (Task 1), the J calculation for surface (Task 2) and through wall (Task 3) cracks in pipes, J calculation in cracked elbows (Task 4), J calculation in particular cases (Task 5) and in welded joint (Task 6).

1. BENCHMARK OVERVIEW

Seven tasks have been defined for the benchmark BENCH-KJ. The aim is to considered conventional and simple situations in the first steps and then to go deeper in the difficulties by analysis of more specific cases. A first set of cases (case means here a reference solution) has been defined by CEA to build the technical work, but all partners was invited to propose additional ones. Each partner was free to propose only partial contributions. As the participation of the benchmark is based only on in-kind financing, the content of each task has been defined to limit the effort of each partner.

This benchmark focuses on analytical procedures but partners can also provide F.E. results, which will be compared to the reference solution. The reference solutions used to define the original cases come from the F.E. database developed jointly by AREVA, CEA and EDF in the frame of defect assessment procedures development and related compendia of the RSE-M and RCC-MRx codes. 2D and 3D F.E. calculations have been performed on cracked piping components (pipes and elbows). This database includes more than 600 different reference solutions.

All applications follow the rules of a blind test: the reference solution for a task is not communicated to the partners before the deadline fixed for the results submission. Each partner is free to provide an update of his results if an error is detected. At the beginning of the benchmark, each partner received anonymously a participant number.

CEA	*France*	**IGCAR**	*India*	**Seoul University**	*Korea*
AREVA	*France*	**CRIEPI**	*Japan*	**GRS**	*Germany*
EDF	*France*	**ENEA**	*Italy*	**Zentech International Ltd**	*UK*
TWI	*UK*	**NPIC**	*China*	**SERCO**	*UK*
BE	*UK*	**RINPO**	*China*	**VTT**	*Finland*
SSM	*Sweden*	**VEIKI Energia**	*Hungary*	**CSN**	*Spain*
INSPECTA	*Sweden*	**KFKI AEKI**	*Hungary*	**Tractebel**	*Belgium*
Frazer-Nash	*UK*	**BAY-LOGI**	*Hungary*	**JAEA**	*Japan*
NRC	*USA*	**IAM Brno**	*Czech Republic*	**KAERI**	*Korea*
BARC	*India*	**JRC Petten**	*Netherlands*		

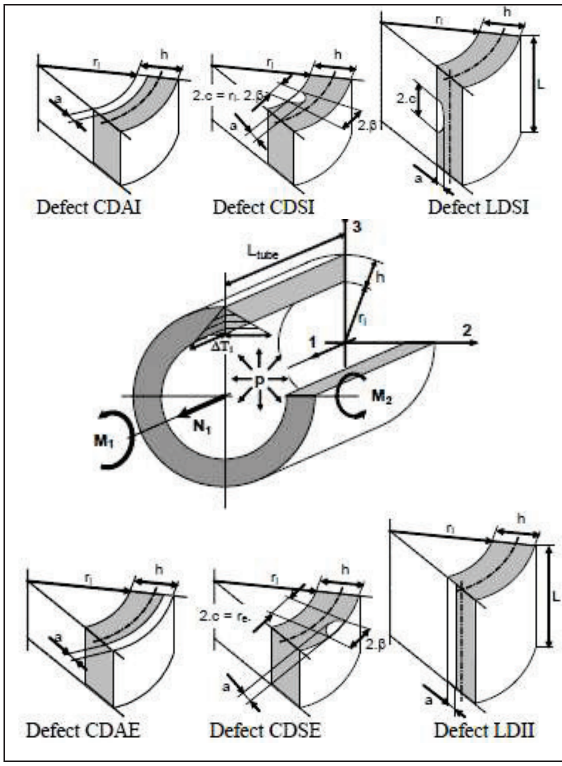
Table 1: List of benchmark participant

The different task and their main results/analysis are presented hereafter.

2. TASK 1: ELASTIC K_I EVALUATION

2.1 Task presentation

The first task consists in a comparison of different procedure to evaluate the stress intensity factor K_I considering two main geometries: cracked (longitudinal or circumferential) pipe under mechanical loading and cracked plate under thermal loading (exponential distribution of elastic nominal stress). Several crack depths have been considered (4 for pipes, 8 for the plate). 21 contributions have been received, with 11 completed on all cases. Main answers are based on AFCEN codes and ASME P&PV Code (see figure 1).



GEOMETRY					
Geometry #	Defect	a/h	c/a	h (mm)	De (mm)
PIPE 1	CDAI – circumferential internal axisymetric	0.1 – 0.25 – 0.5 – 0.75	-	60	660
PIPE 2	CDAE – circumferential internal axisymetric	0.1 – 0.25 – 0.5 – 0.75	-	60	660
PIPE 3	CDSI – circumferential internal semi-elliptical	0.1 – 0.25 – 0.5 – 0.75	3	60	660

GEOMETRY					
Geometry #	Defect	a/h	c/a	h (mm)	De (mm)
PIPE 1	LDII – longitudinal internal infinite	0.1 – 0.25 – 0.5 – 0.75	-	60	660
PIPE 2	LDSI – longitudinal internal semi-elliptical	0.1 – 0.25 – 0.5 – 0.75	3	60	660

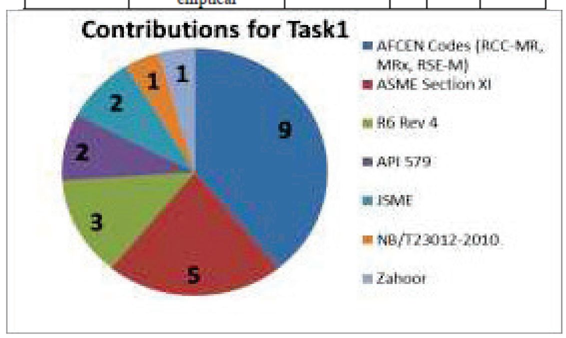


Figure 1. Investigated geometries and codes used for Task1

2.2 Task results and analysis

Main conclusions on this task are the following:

- For cracked pipes, AFCEN codes, R6 and API provide in general relatively correct estimation in comparison to the F.E. reference solution (less than max ± 10%).
- JSME code provides also close results but systematically under predict the F.E. solution, however but the observed differences remains nevertheless less than -10%
- Zahoor solution is in general relatively good agreement, but the difference with F.E. calculation is sometime larger than the 4 first others codes.
- ASME results are really problematic (see figure 2): an important variability is obtained and results are far from reference solution (the results obtained with the other codes are shown at the right side of figure 2). It is important to note that the available solutions are known: the discrepancies are mainly linked to code user errors. Some of them have been identified but the work requested to correct the predictions based on the ASME solution has not been performed.
- For the plate case with an exponential nominal elastic stress distribution, except surprising results provided by some partners, all codes (bases on a polynomial representation of the nominal stress) provided very comparable results and are all over predicting F.E. reference solutions.

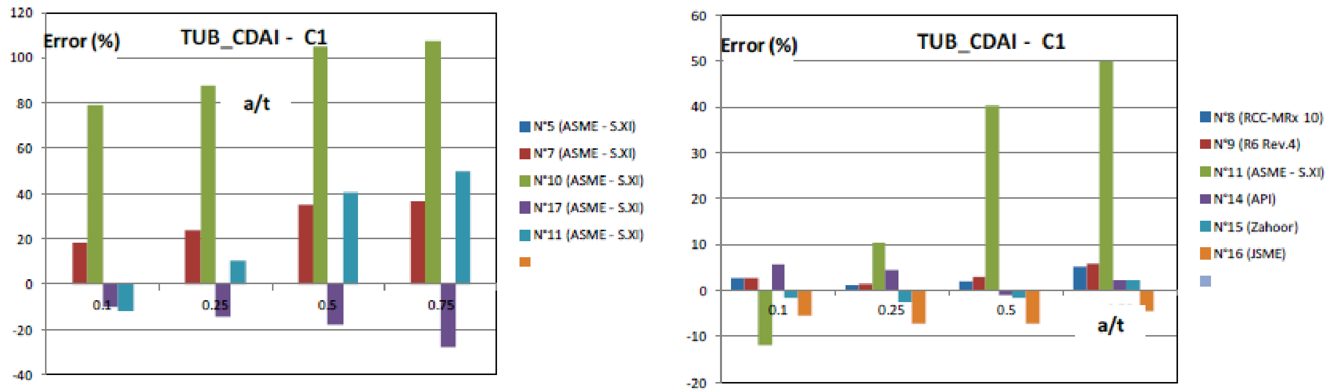


Figure 2. Example of ASME results discrepancy and comparison between codes (error vs F.E. solution)

3. TASK 2 AND 3: J FOR SURFACE AND THROUGH WALL CRACKS IN PIPES

3.1 Tasks presentation

Task 2 and 3 are quite similar and deal with J calculation for surface cracks (Task 2) and through wall cracks (Task 3):

- Task 2: 4 sub-tasks depending on type of defect and loading conditions have been defined :
  - Circumferential surface cracks submitted to mechanical loadings (P, M_2, M_1) (11 cases).
  - Longitudinal surface cracks submitted to mechanical loadings (P, M_2, M_1) (9 cases).
  - Elementary thermal loads i.e. imposed through thickness temperature variation with linear (ΔT_1) and quadratic component (ΔT_2) (7 longitudinal defects and 14 circumferential defects).
  - Combined mechanical plus thermal load conditions (5 longitudinal defects and 6 circumferential defects).

  14 contributions has been received,
- Task 3: 4 sub-tasks of pipes submitted to mechanical load have been considered. 9 partners sent a complete contribution for Task 3 based on analytical solution.

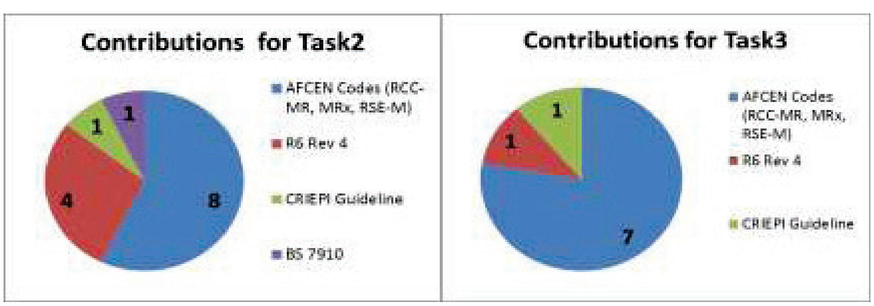


Figure 3. Task 2 and 3 contributions

3.2 Task results and analysis

3.2.1 Task 2

Main conclusions on task 2 are summarized below:

- For mechanical loading (see illustration on figure 4): AFCEN codes lead to homogeneous results except isolated singular error (such as partner 20 on case C4 on figure 4). Considering R6 users, it seems difficult to give a global trend because of important differences between the sets of results. It can be noticed that only two R6 users sent results for longitudinal defect (partner 6 and 9) which are far below F.E. solution (one order of magnitude at Lr,max). Note that BS 7910 user provides such conservative values that he could not provide values for maximum level of load.

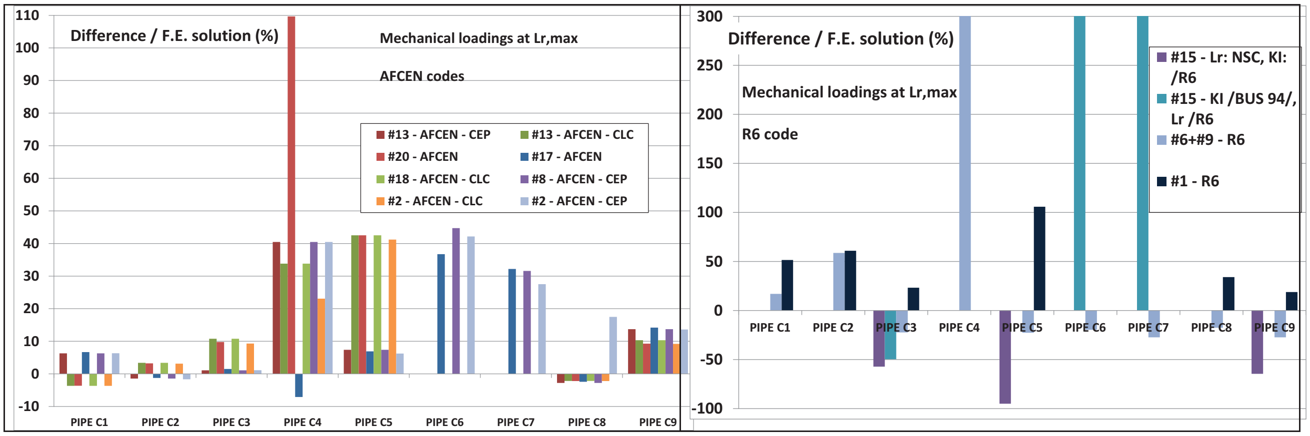


Figure 4. AFCEN and R6 users results compared to F.E. reference for circumferential defect in pipe under mechanical load (at maximum level Lr,max)

- For pure thermal loading: AFCEN codes provide in general a slight conservative prediction, compared to the reference F.E. solutions. R6 code (applied considering the elastic solution for J) provides more conservative results. BS 7910:2005 results are the most over-conservative (probably linked to a user error not investigated yet)

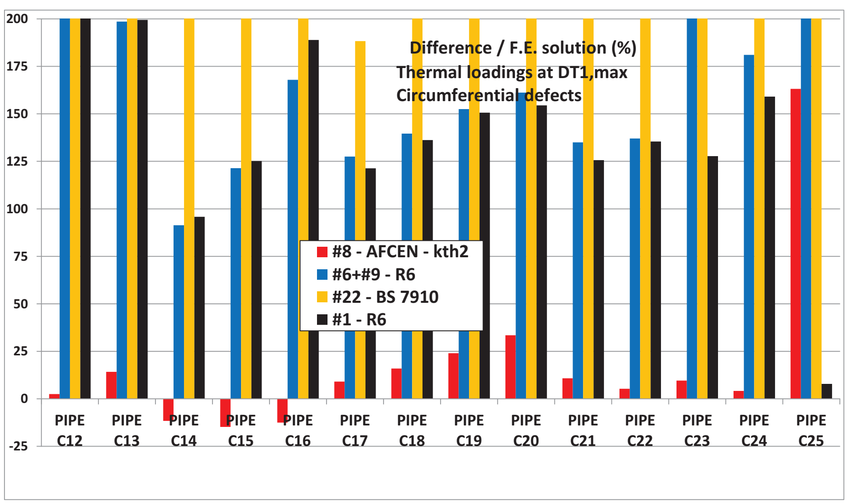


Figure 5. Illustration of results obtained on circumferential defect under pure thermal loading

- For combined thermal plus mechanical loading: conclusions are the same than for pure thermal loading.

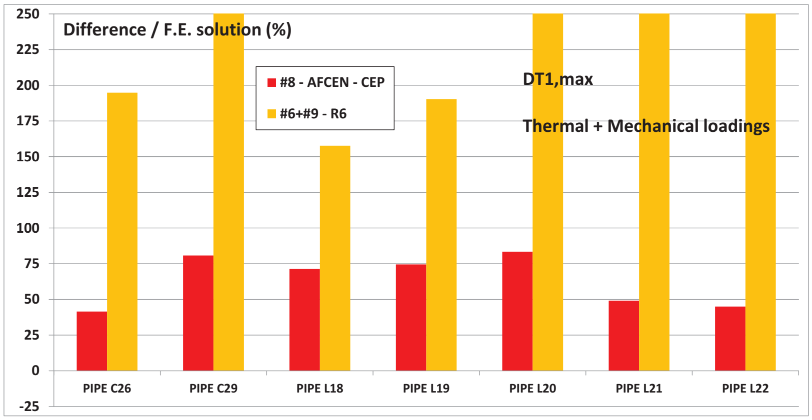


Figure 6. Comparison between representative results of one AFCEN user and R6 one's for cases submitted to combined thermal and mechanical loadings

3.2.2 Task 3

Figure 7 compares the difference at maximum load level (Lr, max) between AFCEN solutions and reference F.E. result on the left side and between one representative AFCEN user (#8) and other codes on right side. A good homogeneity of the AFCEN results is observed. Only partner 3 provided "singular" results. Besides it could be noticed than R6 and AFCEN codes lead to comparable results whereas CRIEPI Guideline results are very low compared to the other ones.

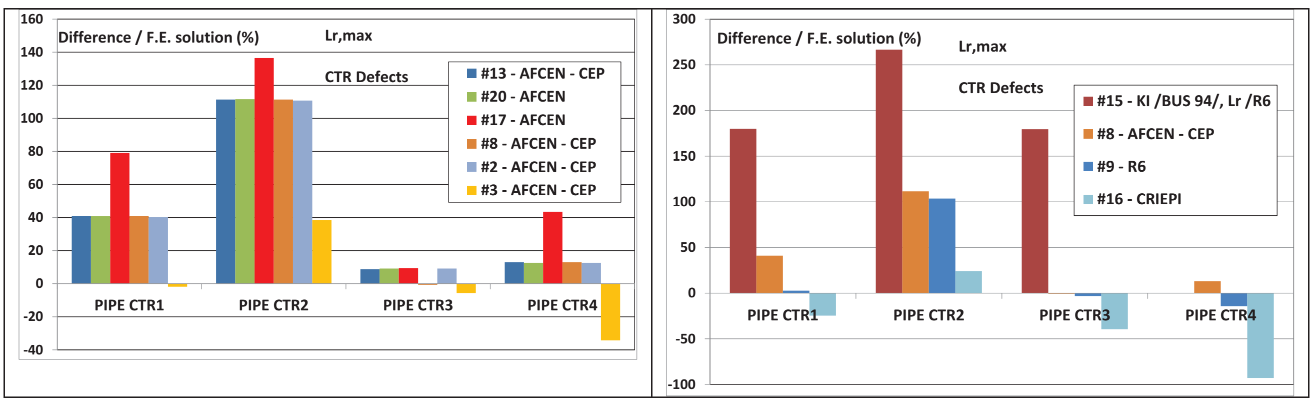
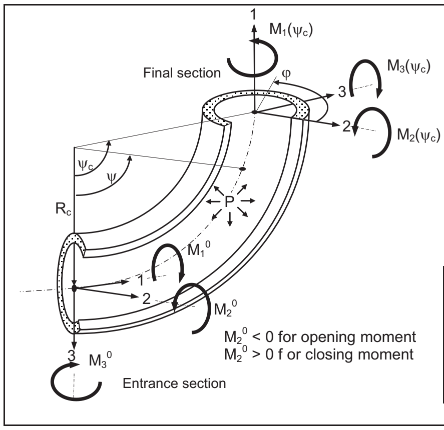


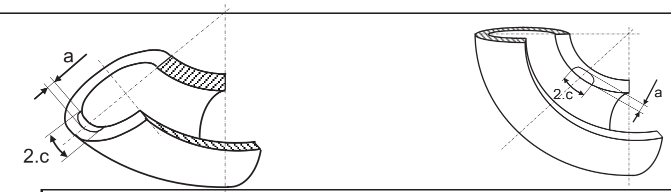
Figure 7. Comparison of results obtained on pipes with through wall crack under mechanical loading

5. TASK 4: J IN CRACKED ELBOWS

5.1 Task presentation

This task focuses on the analytical calculation of the J parameter for circumferential or longitudinal cracks in elbows submitted to mechanical, thermal or combined loadings. Figure 8 and Table 2 give a quick overview of considered configuration and codes used for this task.





		Load							
		Single mechanical			Combined mechanical			With thermal	
		P	M2	M3	P+M2	M2+M3	M1+M3	deltaT	M2+deltaT
Defect type		1			1				
Circumferential	CDAI	1		1					
9 cases	CDSI					1			1
longitudinal	LDII	1	1						
8 cases	LDSI	1			1	1		1	1
	LDSE		1						

Figure 8. Task 4 general geometries and contributions

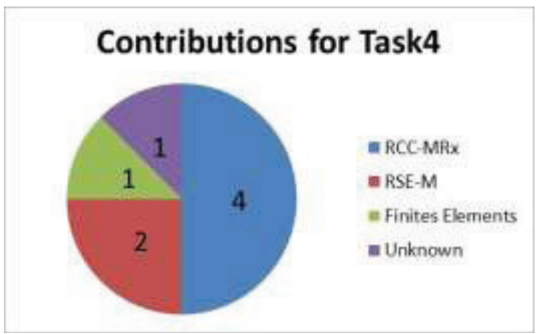


Table 2: Task 4 contributions

8 partners provided results for this task, one partner (#14) provided F.E. results which lead to important differences with benchmarked reference solutions and is consequently not considered in the following analysis. Most contributions are based on AFCEN code (RCC-MRx, RSE-M) which share the same scheme regarding of fracture mechanics tools.

5.2 Task results and analysis

Comparisons have been done for elastic value of J, J_{el}, and elastic-plastic correction (J_{pl}/J_{el}) in order to uncouple elastic and elastic-plastic consideration (AFCEN codes are based on an amplification of J_{el} to evaluate J_{pl}). Illustrations given on following figures are relative to on maximal loading conditions but conclusions are the same for the whole load history.

- Considering Elastic value of J:
  - For mechanical load: results are globally homogeneous and J values are well predicted considering pressure loading conditions whereas bending and torsion moment implies more discrepancy especially in the cases of circumferential defect. In such cases J may be largely over or under predicted (except partners 8 and 19, see left side on Figure 9) which may be due to the section considered (median one instead of entrance).
  - Under thermal and combined load, a good homogeneity of the results is obtained for each case and the reference elastic solution is underestimated by all the partners (see right side on Figure 9). It is due to the fact that only linear through-thickness temperature variation is

proposed in the J elastic solution, whereas the considered cases correspond to a non linear variation. This point shall be improved in the future to be able to deal with these configurations.

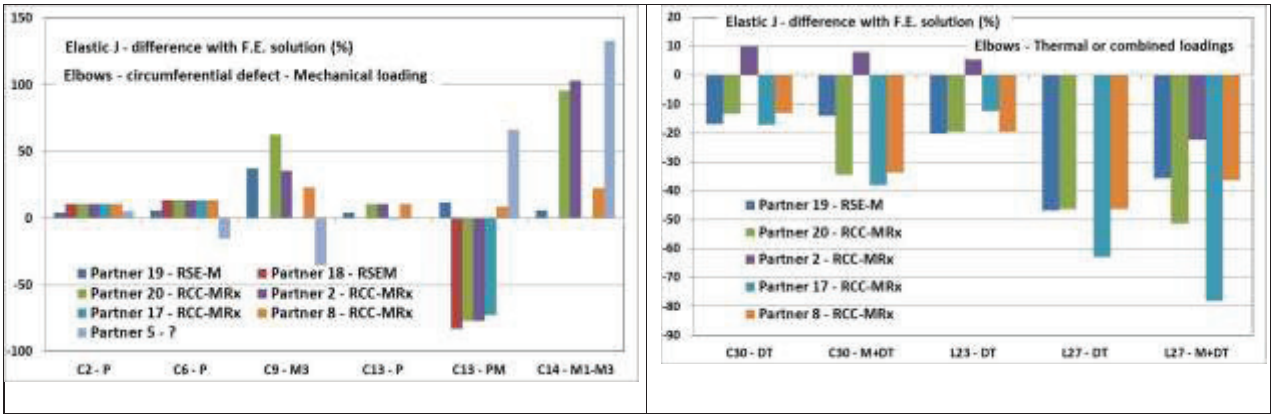


Figure 9. F.E. vs analytical solutions for elastic value of J in cracked elbow submitted to mechanical (left side) or thermal/thermal+mechnical load

- Considering Elastic-plastic correction:
  - For mechanical load, results are good agreement considering that two groups can be observed, due to the option (CEP or CLC options available in AFCEN codes) selected by the partner. As for elastic value, a little more variability is obtained for bending moment compared to pressure load.
  - Under thermal load, contributions are globally homogeneous except particular results such as plotted on Figure 10 for partner 20 and 17 when thermal load is combined with bending moment.

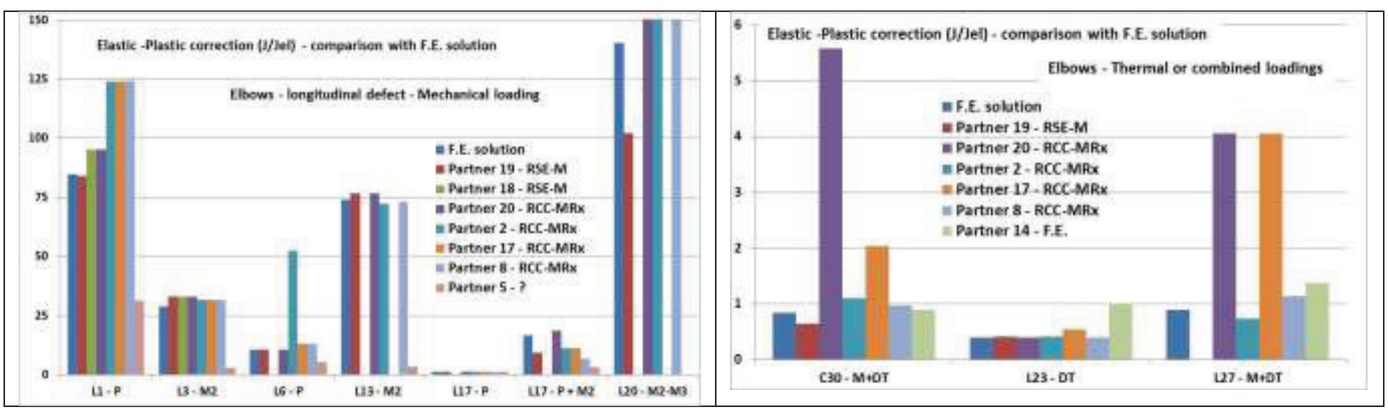


Figure 10. Comparison of analytical plastic correction and F.E. reference computation (first drawbar) for elbows with a longitudinal defect under mechanical load (left side) and

6. TASK 5: PARTICULAR CASES

6.1 Task presentation

Two sub-tasks are considered in this paper (due to a lack of contribution on two other ones):

- The first one consist in the evaluation of elastic-plastic value of J in a cracked pipe (one configuration considering a circumferential axisymmetric defect) submitted to an axial displacement. Only one partner (partner 8) provided analytical solution using RCC-MRx procedure, all others used F.E. calculations.
- The second one consists in evaluating elastic value of J in a plate containing an embedded elliptical defect under combined axial load and bending moment. Four partners provided results, all based on appendix A16 of RCC-MRx except partner 14 who performed Finite Element calculations.

6.2 Task results and analysis

For the first sub-task dedicated to an imposed displacement loading on a cracked pipe, solutions are given on Figure 11 (left side). Partners 8 and 3 get similar F.E. results whereas there are some differences with partner 17. The RCC-MRx solution (in red in Figure 11) appears to be a conservative but reasonable solution. The highest difference is observed at the onset of the plasticity. When the plasticity is fully developed, the analytical solution gets closer to the F.E. solution.

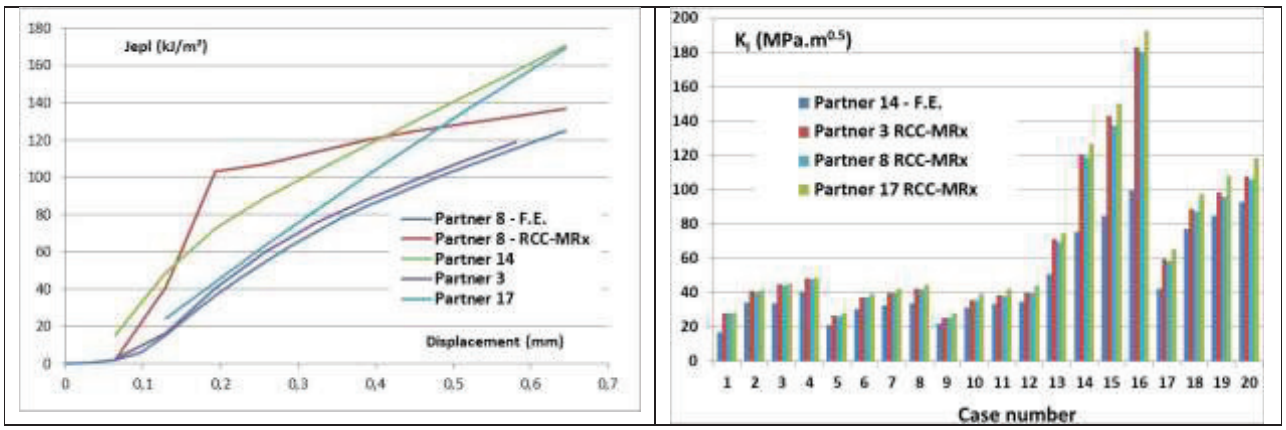


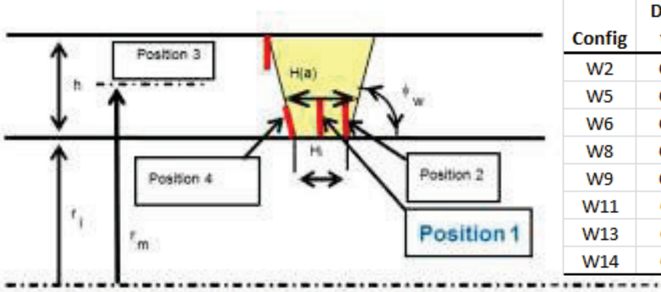
Figure 11. Elastic-plastic value of J for imposed displacement case (left side) and synthesis of comparison between F.E. solution (#14, first drawbar) and K_I analytical results for embedded defect (right side)

For embedded cases (right side on Figure 11), all partners provided very close results. The fact that partner 17 obtained slightly higher values can be explained by the fact that partner 17 used 2010 code version which has been updated in terms of nominal stresses compared to the previous edition.

7. TASK 6: J IN WELDS

7.1 Task presentation

Task 6 focuses on cases with a circumferential crack in the middle of a weld (see position 1 on Figure 13). No residual stresses (RS) consideration was recommended in this task, but one partner (partner 6) used R6 Section IV compendium to introduce RS profile.



Config	Defect type	Weld angle	a/h	Defect length/depth	Mismatch
W2	CDAI	90	0,25		1,5 (Rambert-Osgood)
W5	CDAI	90	0,25		2,3 (Rambert-Osgood)
W6	CDAI	90	0,0625		2,3 (Rambert-Osgood)
W8	CDAI	60	0,25		2,3 (Rambert-Osgood)
W9	CDAI	60	0,25		2,3 (Bilinear)
W11	CDSI	60	0,0625	2	2,3 (Rambert-Osgood)
W13	CDSI	60	0,25	2	2,3 (Rambert-Osgood)
W14	CDSI	60	0,25	2	2,3 (Rambert-Osgood)

Figure 13. Weld joint geometry and cases considered

Mechanical load (axial, internal pressure and bending moment) have been considered. The number of configuration have been reduced to 8 but only 3 partners provided results on all 8 cases (considering 2 gave only F.E. results). Codes used in this task are:

- AFCEN code (RCC-MRx, note that AFCEN code users provide results using both two available option in RCC-MRx, CEP and CLC),
- R6 rev 4 (including RS contribution),
- One partner (partner 15) used a DFH-ETM-SINTAP method which stands for Ductile Fracture Handbook (for K_I) associated to Engineering Treatment method modified for weld (for the limit load) and SINTAP Procedure (FAD curve).

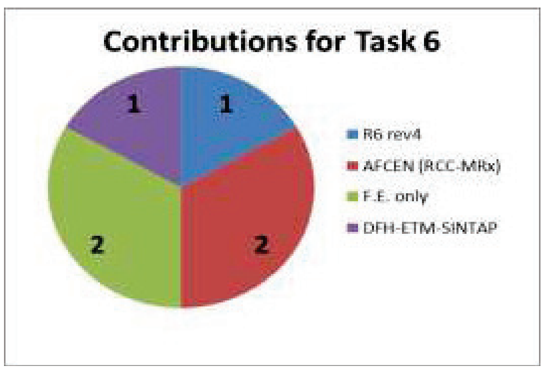


Figure 14. Task 6 contributions

7.2 Task results and analysis

Due to the task complexity, only 5 partners contributed using analytical method and most of them performed F.E. computations in the same time.
Figure 15 shows the results obtained at higher level of load (Lr_max) on 8 cases. Green and red lines correspond respectively to exact solution ($J=J_{F.E.\ ref}$) and to a two ratio ($J=2.\ J_{F.E.\ ref}$).
AFCEN code users provide exactly the same results on both CEP and CLC option, which appears to be conservative on all 8 cases. It can be noticed that CLC option seems to give closer results on the studied cases but there is too few configurations to generalize this point. R6 user is also conservative on all cases except on W9 which seems to conduct to large discrepancy, keeping in mind concerned partner took into account residual stresses. DES user provided singular results (very low value of J) on both cases W8 and W9. It can be noticed that right side of Figure 15 shows that there is also no satisfactory agreement on Finite Element computations performed on these cases.
Except these configurations, results range (in terms of elastic-plastic value of J at maximum level of load) between the reference solution and twice this reference value.

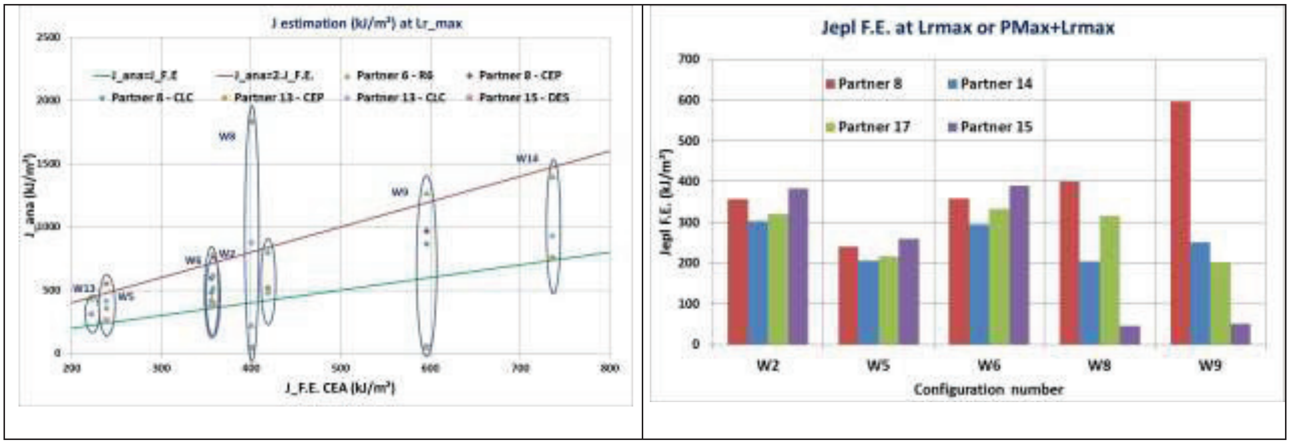


Figure 15. J values at maximum load condition (Lr_max) considering analytical solutions (left side) and F.E. computations (right side, reference solution is given by partner 8)

8. CONCLUSION

This paper presents the work performed in the "BENCH-KJ" benchmark launched in the frame of the OCDE/IAGE METAL group on fracture mechanic parameters calculation. It appears to be a complex exercise, given that a particular attention must be paid on the first step of benchmark definition which needs to be as exhaustive as possible (contributors and used codes aren't known in advance). Twenty-nine partners are globally involved, level of contribution depending on the considered technical task keeping in mind that it relies on in-kind participations. Main conclusions are the following:

- Task 1 - K_I: considering different codes used, results are globally homogeneous and in good agreement with F.E. reference solutions but some discrepancy persists, in particular with ASME users.
- Tasks 2 and 3 - J in cracked pipes: AFCEN codes users globally provided homogeneous results, and in good agreement with F.E. solutions whereas much more discrepancy is obtained between R6 users. Thermal load sometimes leads to large over-estimated J value (in particular for BS and R6 rules).
- Task 4 - J in cracked elbows: for such complex geometry considering analytical solutions, only AFCEN codes have been used and lead to similar results between partners with some restriction for bending moment.
- Task 5 - particular cases: only one analytical contribution has been received for imposed displacement consideration (AFCEN code which gives satisfactory results). In the same way, for embedded crack cracks, only RCC-MRx has been used and conduct to homogeneous value of K_I.
- Task 6 - J in weld: for this last technical task, even if the number of cases have been reduced through benchmark progress, the number of contribution was small and task difficulty seems to encourage contributors to perform F.E. computations in parallel, which may also show some unexplainable discrepancies. R6 and AFCEN users provided conservative results, keeping in mind that the R6 contributor considered residual stresses.

Generally speaking, the bench KJ exercise does not aim to a deep analysis of code accuracy given that this benchmark relies on in kind contribution (contributions and their analysis are in fact time consuming), some approaches were based on "mixed" methods, skill level of participants goes from PhD to fracture mechanics expert, some partners provided updated results others not… It constitutes a great way for young engineers to be trained on analytical tools in fracture mechanics but it also highlighted than even these sometimes called “simplified” tools can be complex to use, sources of human errors being multiple.

That’s why it can be understood that there is a real need for codes to be as prescriptive as possible in order to avoid such human errors as load considerations (for example pressure on crack tips, clear orientation of bending moment, ratio two on imposed displacement…), localization of defect (different section possible in elbows). The challenge consists in conciliating this requirement of sufficient guidance with an acceptable ease of use. For this purpose, note that for AFCEN codes like RCC-MRx Appendix A16 or RSE-M Appendix 5.4 such “software” already exists (as an example CEA developed MJSAM software which is freely distributed and provided all fracture mechanics methods of A16). Such initiatives may ease and improve reliability of codes uses and allow deeper analysis on code accuracy.

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