Alma Mater Studiorum

Design of Experiment and applications to research

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OUTLINE

- Some biographical notes
- Research topics
- Applications of DOE to research in engineering: *ANOVA, Pairwise Tests, augmented ANOVA*

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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University of Bologna

9 centuries of History (since 1088)

Multi-campus University

4,911

Third cycle:

- PhD: 1481
- Specialisation Schools: 1323
- Professional Master: 1448
- Postgraduate/Lifelong learning Programmes: 659

84,744

TOTAL

Degree Programmes:

- First cycle degree Programmes: 56,9%
- Second cycle degree Programmes: 20,3%
- Single cycle degree Programmes: 20,2%
- Degree programme under previous system: 2,6%

TOT

2,781

Professors:

- Full Professors
- Associate Professors
- Assistant Professors

BIOGRAPHICAL NOTES

Ph.D. in Mechanics of Materials and Technological Processes

Assistant Professor of Machine Design since 2008

Research topics:

- High and Low cycle Fatigue, surface treatments (shot-peening).
- Experimental Mechanics and in-field tests.
- Reliability assessments based on experimental data.
- Bolted and adhesively bonded joints.

INTRODUCTION

- How the treatment parameters may affect the fatigue response
- How the manufacturing process may affect the low cycle fatigue response
- How the engagement ratio may affect the shear strength of an adhesively bonded joint.
- How lubrication may affect the preload of a bolt.

Impact of a factor on an output…

Design of experiment

Input and output variable choice. Test arrangement

Statistical analysis of the yields.

INTRODUCTION

The principles and techniques of experimental design transcend the area of their application; the only difference from one application area to another is that different situations arise with different frequency, and correspondingly, the use of various design and design principles occurs with different frequency.

P.D. Berger, R.E. Maurer, “Experimental Design with Applications in Management, Engineering and the Sciences”, Duxbury Thomson Learning, 2002

- Design of Experiment (DOE) techniques can by applied to many fields of science
- Experimenting and DOE is part of everyday life.
- Different techniques with different suitability

INTRODUCTION

Experimentation? Part of our life!

Will leaving 30 minutes before my appointment let me find a good and legal parking? And what about 20 or 10?

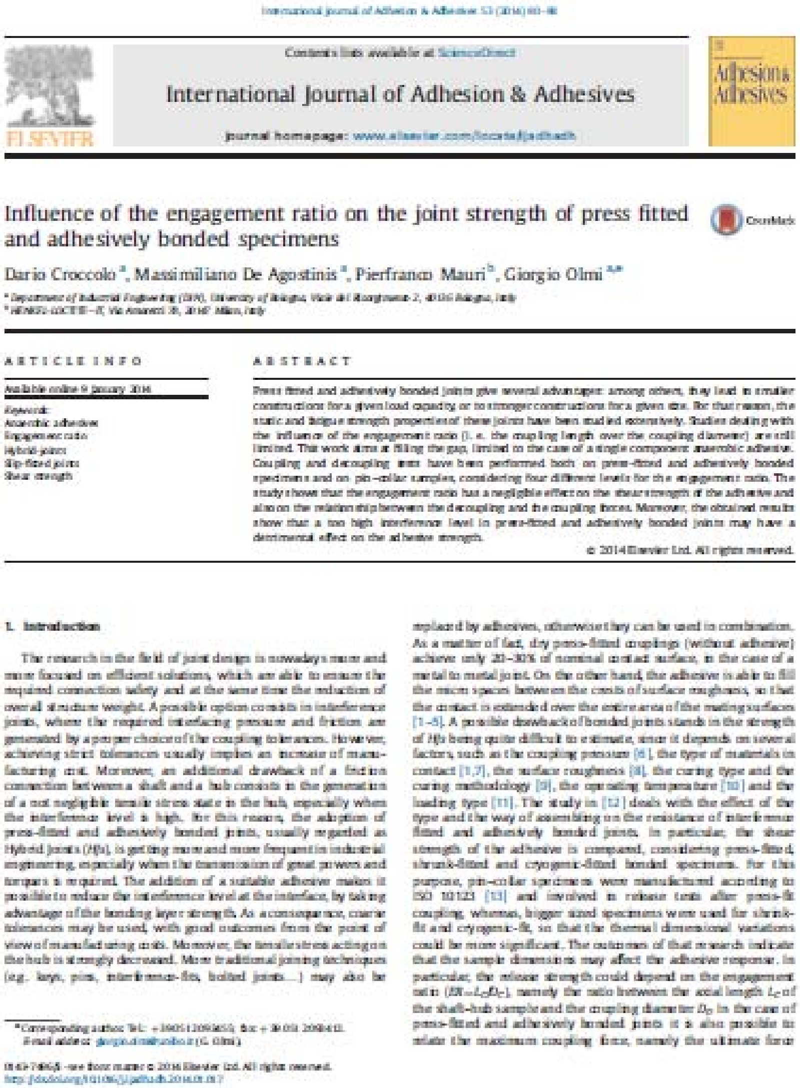
INTRODUCTION

Experimentation? Part of our life!

Former «Palafitte» classrooms (Faculty of Engineering, Bologna) while being dismantled

Will arriving two hours before my lesson make me find a good seat? Would one hour or less be sufficient?

CASE STUDY: STRUCTURAL ADHESIVES



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International Journal of Adhesion & Adhesives 53 (2014) 80–88

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

Influence of the engagement ratio on the joint strength of press fitted and adhesively bonded specimens

Dario Croccolo [a], Massimiliano De Agostinis [a], Pierfranco Mauri [b], Giorgio Olmi [a,*]

Available online 9 January 2014

Keywords:
Anaerobic adhesives
Engagement ratio
Hybrid joints
Slip-fitted joints
Shear strength

1. Introduction

What about the shear strength of structural adhesive? May it be dependent on the joint geometry?

If so, what is the best proportioning?

D. Croccolo, M. De Agostinis, P. Mauri, G. Olmi, " Influence of the engagement ratio on the joint strength of press fitted and adhesively bonded specimens", *International Journal of Adhesion & Adhesives*, 53 (2014) 80-88

INTRODUCTION

Design of mechanical joints: safe connection with reduced weight

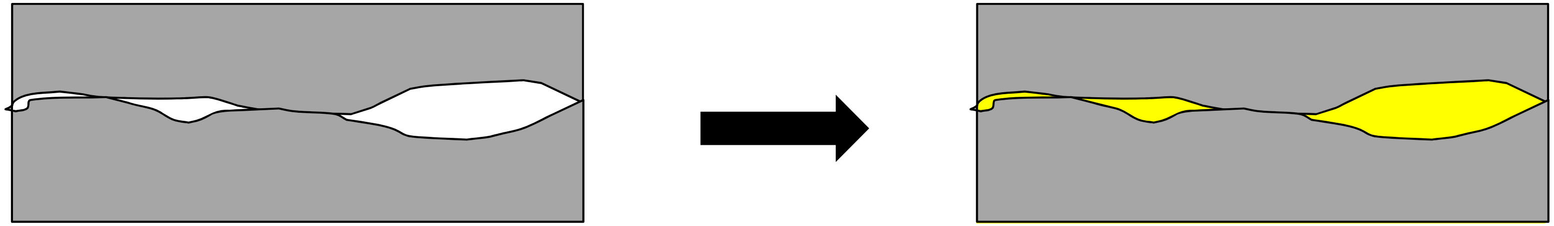
Possible alternatives

Bolts (removable joint, but highly dependent on friction, frictional coefficients my vary following multiple tightenings)

Interference shaft-hub couplings (careful control of tolerances, high tensile load transferred to the hub)

Bonded joints or hybrid joints (by interference and adhesive)

INTRODUCTION



Contact on crests (20-30% overall surface)

Adhesive filling the voids

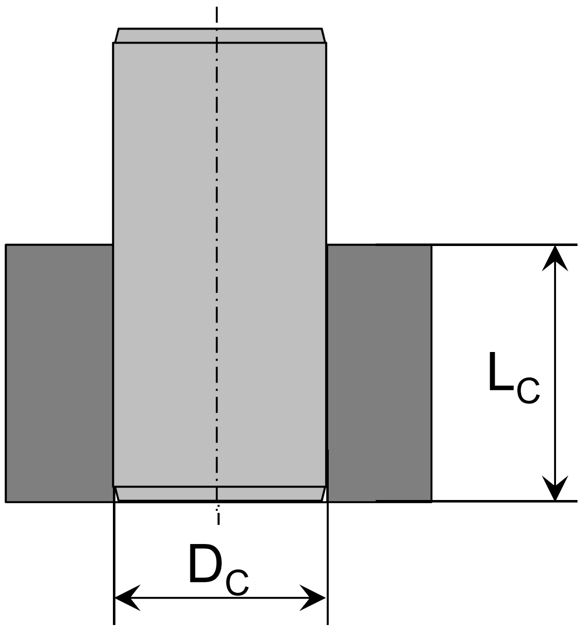
Subject:

Problem: Determining the strength of an anaerobic adhesive (LOCTITE648) in a hybrid joint

Experimentally measurement of the adhesive strength for different joint proportioning

Comparing the results: influence of the L/D ratio on strength

INTRODUCTION



$$\tau_{ad} = \frac{F_{tot.} - F_{attr.}}{A} = \frac{F_{ad}}{A}$$

$$A = \pi D_c L_c$$

ISO 10123: specimen with $L_c/D_c = 0.8$

In theory $\tau_{Ad.}$ (=adhesive shear strength) is independent of geometry

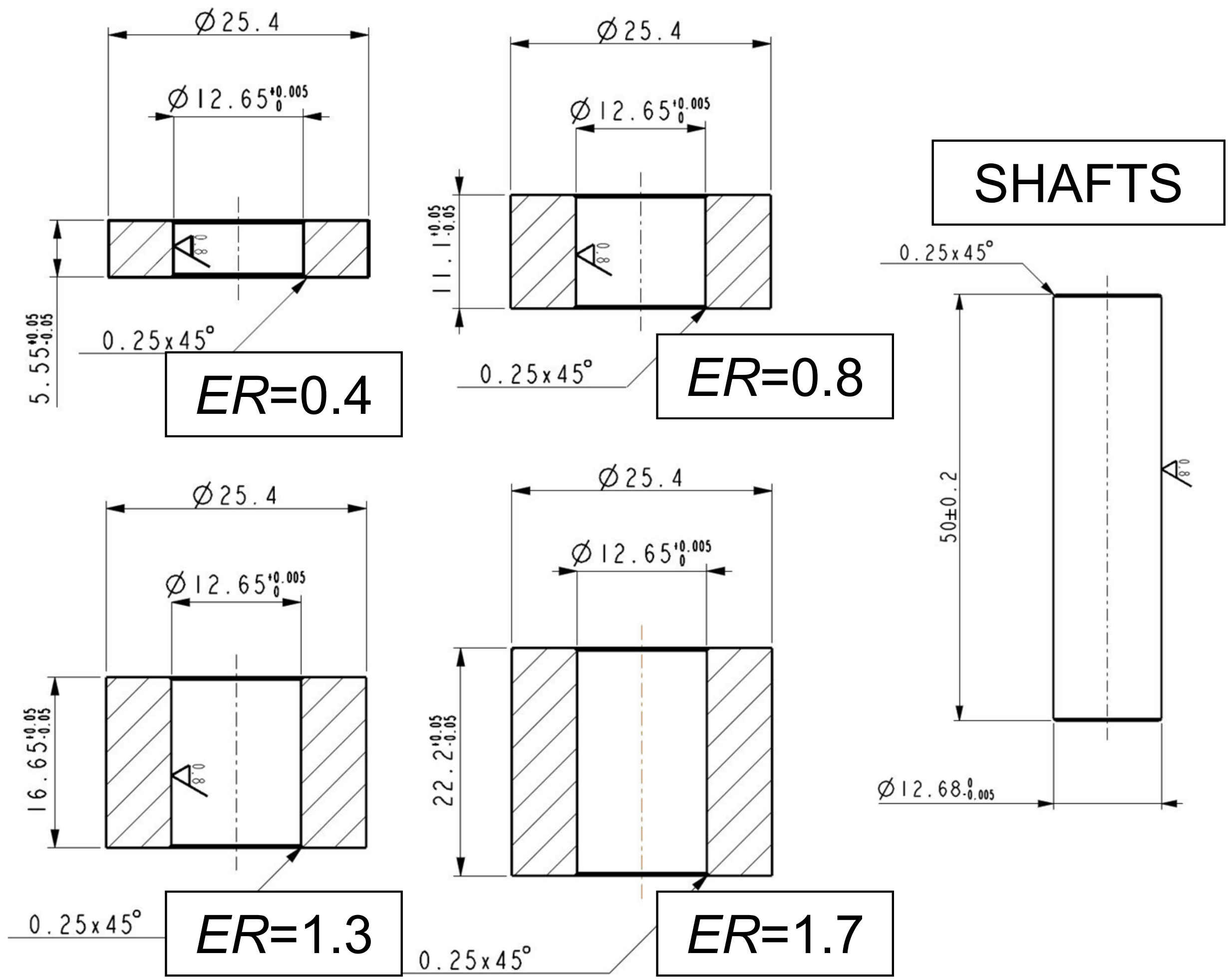
Previous studies indicated a possible dependence on $ER=L_c/D_c$

METHODS

Determining the impact of L_c/D_c:

Four different levels: from half of 0.8 to the double

Hubs of 4 different dimensions



METHODS

One factor, $ER=L_c/D_c$, evaluated at 4 levels:

0.4; 0.8; 1.3; 1.7

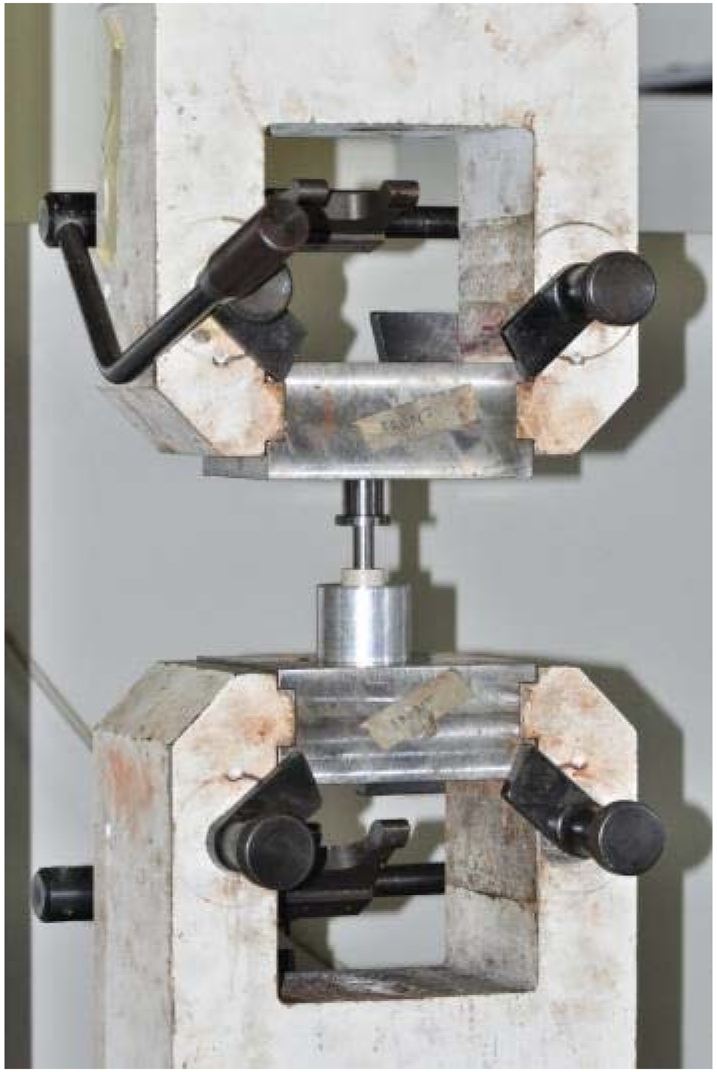
10 sample per level (10 replications)

Some results had to be discarded due to not conformal failures

One-factor ANOVA

Possible refinement of results only in the case of significant differences

EXPERIMENTAL PROCEDURE



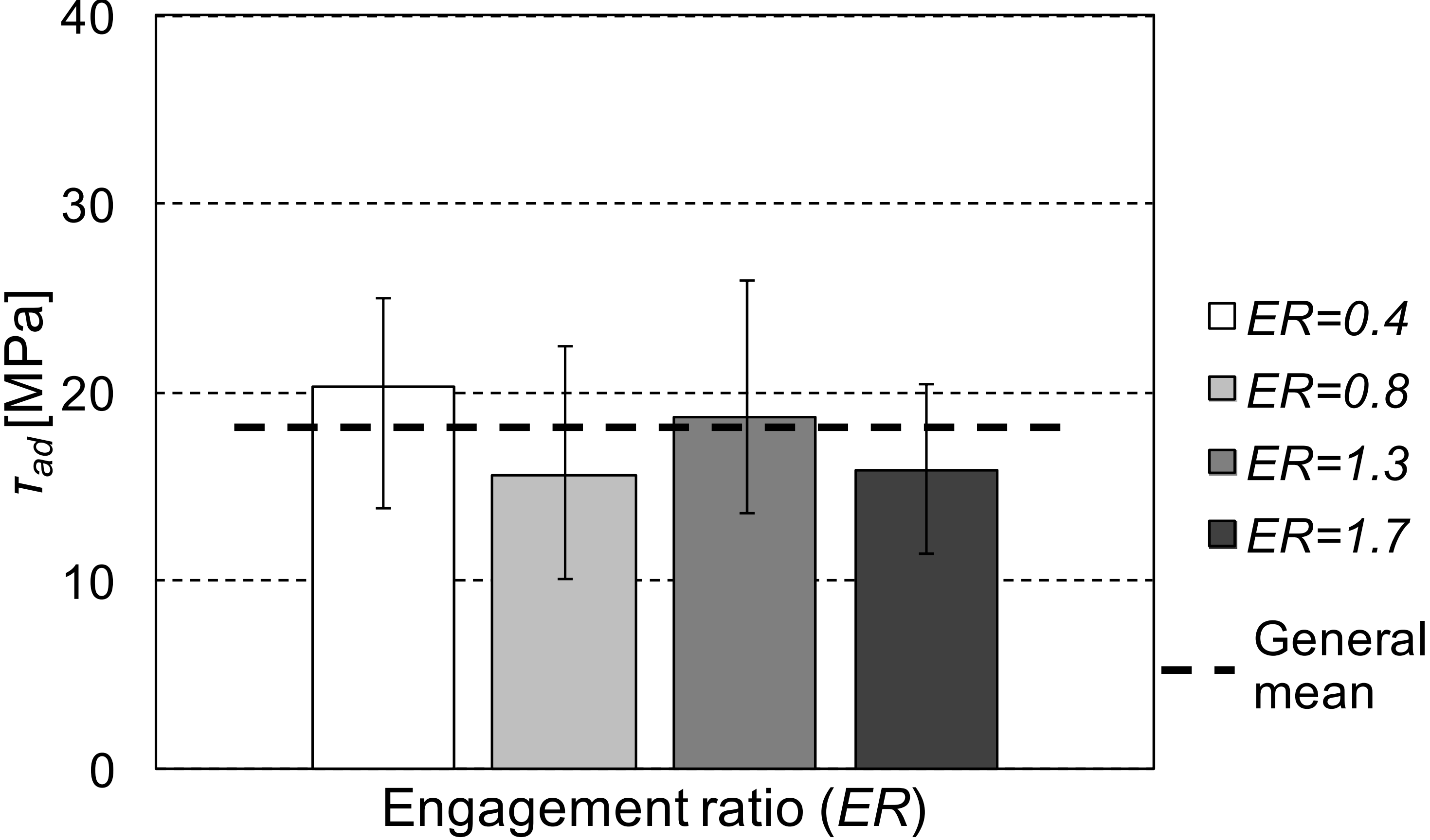
RESULTS

High interference: 18μm

Low interference: 6μm

RESULTS

Differences involving the mean values, but variation intervals almost overlapped
→ ANOVA



BRIEF NOTES ON ANOVA

i = 1, … , R, number of replications (10 in the ex.)
j = 1, … , C, number of levels (4 L/D ratios in the ex.)

$$\underbrace{\sum_{j=1}^{C}\sum_{i=1}^{R}\left(Y_{ij}-\overline{Y}_{..}\right)^2}_{\textbf{TSS}} = \underbrace{R\cdot\sum_{j=1}^{C}\left(\overline{Y}_{.j}-\overline{Y}_{..}\right)^2}_{\textbf{SSB}_C} + \underbrace{\sum_{j=1}^{C}\sum_{i=1}^{R}\left(Y_{ij}-\overline{Y}_{.j}\right)^2}_{\textbf{SSW}_C}$$

TSS: Total Sum of Squares (Total variance)

SSB_C: Sum of Squares Between Columns

SSW_C: Sum of Squares Within Columns

SUM OF SQUARES

$$TSS = \sum_{j=1}^{C} \sum_{i=1}^{R} \left(Y_{ij} - \overline{Y}_{..} \right)^2$$

Total variance due to the considered factor and to experimental uncertainty (error)

SUM OF SQUARES

$$SSB_C = R \cdot \sum_{j=1}^{C} \left(\overline{Y}_{.j} - \overline{Y}_{..} \right)^2$$

Variance due to the
impact of the
considered factor (X)

SUM OF SQUARES

$$SSB_C = R \cdot \sum_{j=1}^{C} \left(\overline{Y}_{.j} - \overline{Y}_{..} \right)^2$$

Variance related to differences among columns (factor levels) and to the impact of X on Y

R has the meaning of an amplifying coefficient, equal to the number of rows, i.e. of replications. So, the higher is R, the greater is SSB_C. The reliability of a result is proportional to the number of replications to its achievement. Let us suppose that the strength (yield Y) associated to a level of the factor X is much greater than the global grand mean. This result is of poor significance, if I tested just two joints per level, it is a bit higher, if I tested 3, it is much higher if I tested 200.

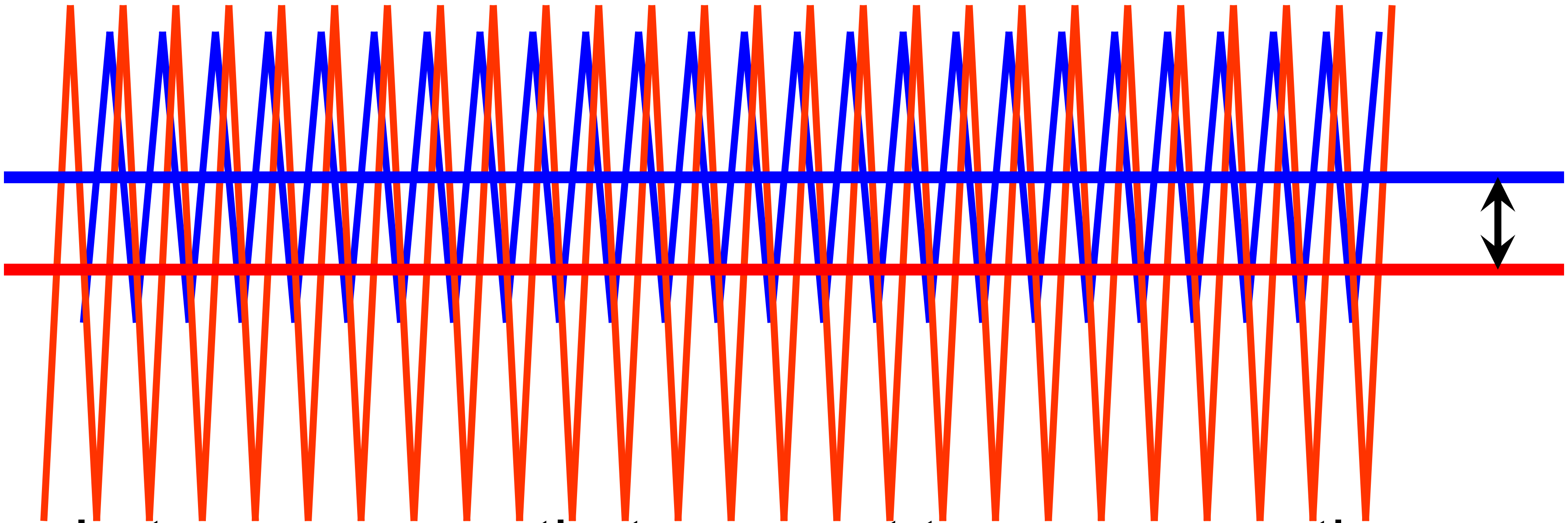
SUM OF SQUARES

$$SSW_C = \sum_{j=1}^{C} \sum_{i=1}^{R} \left(Y_{ij} - \overline{Y}_{.j} \right)^2$$

Variance due to the influence of all factors other than X. They may be environmental factors, such as temperature or humidity in operating conditions. With their fluctuations they are cause of a noise, usually called experimental uncertainty. SSW is sometimes referenced as SSE (E is for “error”).
Should it happen that SSW is very high and very close to the value of TSS, it means that the experimental uncertainty covers the effect of X on Y. On the other hand, in the opposite case (SSW very low and SSB_C almost coincident to TSS), the effect of X on Y is very strong and can be guessed beyond any possible experimental error.

SUM OF SQUARES

Two extreme cases:

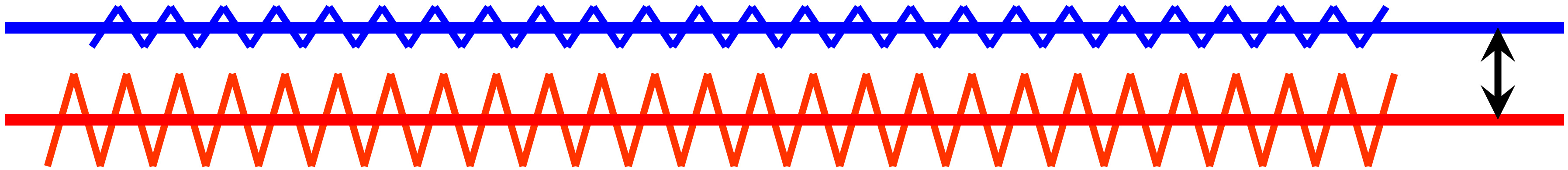


Let us suppose that we want two compare these two signals: mean values are different, but the differences are covered by huge fluctuations (uncertainty).

$SSB_C \neq 0$, but $SSB_C << SSW_C$

SUM OF SQUARES

Two extreme cases:



In this case we have the same mean values but the differences are greater than uncertainties and can be clearly detected

$\mathbf{SSW_C \neq 0}$**, ma** $\mathbf{SSB_C >> SSW_C}$

Fisher’s F-Test to be used for comparisons

FISHER'S F-TEST

We can consider two hypotheses:

H_0 (null hypothesis): The variable X has no influence on the result Y: e.g. the differences among results for different brands are only due to uncertainties (occurred just by a chance)

H_1 (significance hypothesis): The variable X has an impact on the result Y, this influence is can be stated beyond any uncertainty.

H_0 ?? H_1

Statistical Test

RESULTS

	SSQ	DoF	MSQ	$F_{calc.}$	p-v.	c
SSB_C	95.09	3	31.70	1.83	17.4%	3.09
SSW_C	345.96	20	17.30			
TSS	441.04	23				

Only 24 results were actualy considered for processing

- p-v.: probability of getting what we got just be a chance
- When saying significant differences are present → probability of error of 17.4% (not acceptable)
- 5% significance level usually regarded as a threshold
- No significant differences

CASE STUDY: STRUCTURAL ADHESIVES


International Journal of Adhesion & Adhesives 67 (2016) 69–75

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journal homepage: www.elsevier.com/locate/ijadhadh

Influence of the engagement ratio on the shear strength of an epoxy adhesive by push-out tests on pin-and-collar joints: Part I: Campaign at room temperature

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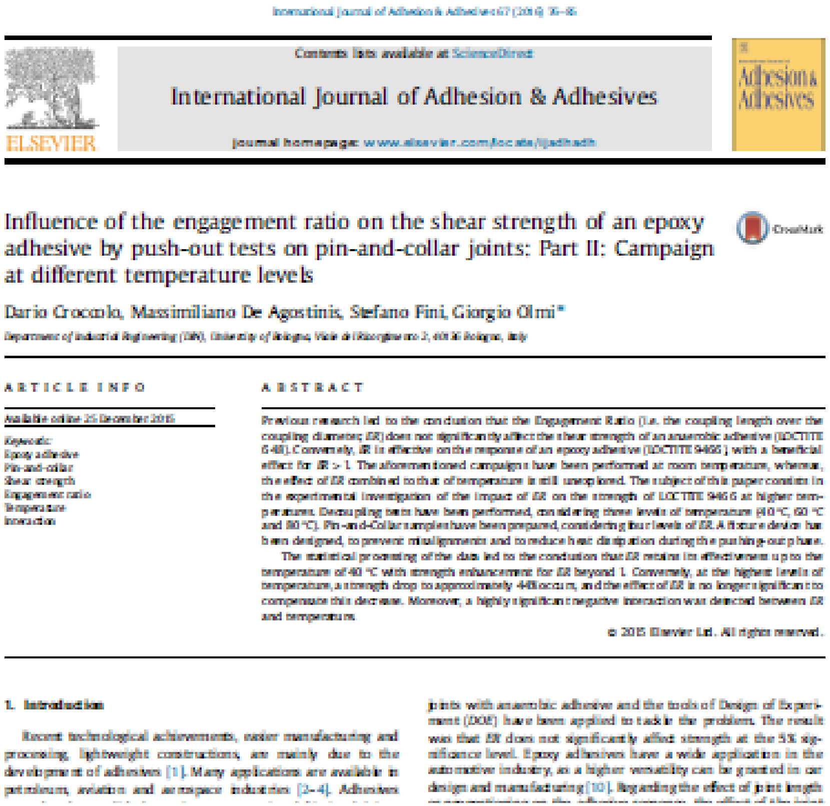
International Journal of Adhesion & Adhesives 67 (2016) 76–85

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

Influence of the engagement ratio on the shear strength of an epoxy adhesive by push-out tests on pin-and-collar joints: Part II: Campaign at different temperature levels

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ARTICLE INFO

Available online 25 December 2015

Keywords:
Epoxy adhesive
Pin-and-collar
Shear strength
Engagement ratio
Temperature
Interaction

ABSTRACT

Previous research led to the conclusion that the Engagement Ratio (i.e. the coupling length over the coupling diameter, ER) does not significantly affect the shear strength of an anaerobic adhesive (LOCTITE 648). Conversely, ER is effective on the response of an epoxy adhesive (LOCTITE 9466) with a beneficial effect for ER > 1. The aforementioned campaigns have been performed at room temperature, whereas, the effect of ER combined to that of temperature is still unexplored. The subject of this paper consists in the experimental investigation of the impact of ER on the strength of LOCTITE 9466 at higher temperatures. Decoupling tests have been performed, considering three levels of temperature (40 °C, 60 °C and 80 °C). Pin-and-Collar samples have been prepared, considering four levels of ER. A fixture device has been designed, to prevent misalignments and to reduce heat dissipation during the pushing-out phase.

The statistical processing of the data led to the conclusion that ER retains its effectiveness up to the temperature of 40 °C with strength enhancement for ER beyond 1. Conversely, at the highest levels of temperature, a strength drop to approximately 44% occurs, and the effect of ER is no longer significant to compensate this decrease. Moreover, a highly significant negative interaction was detected between ER and temperature.

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1. Introduction

Recent technological achievements, easier manufacturing and processing, lightweight constructions, are mainly due to the development of adhesives [1]. Many applications are available in petroleum, aviation and aerospace industries [2–4]. Adhesives

joints with anaerobic adhesive and the tools of Design of Experiment (DOE) have been applied to tackle the problem. The result was that ER does not significantly affect strength at the 5% significance level. Epoxy adhesives have a wide application in the automotive industry, as a higher versatility can be granted in car design and manufacturing [10]. Regarding the effect of joint length

What happens if we change the adhesive type? (Anaerobic→ epoxy)

What is the best proportioning?

What if temperature is increased?

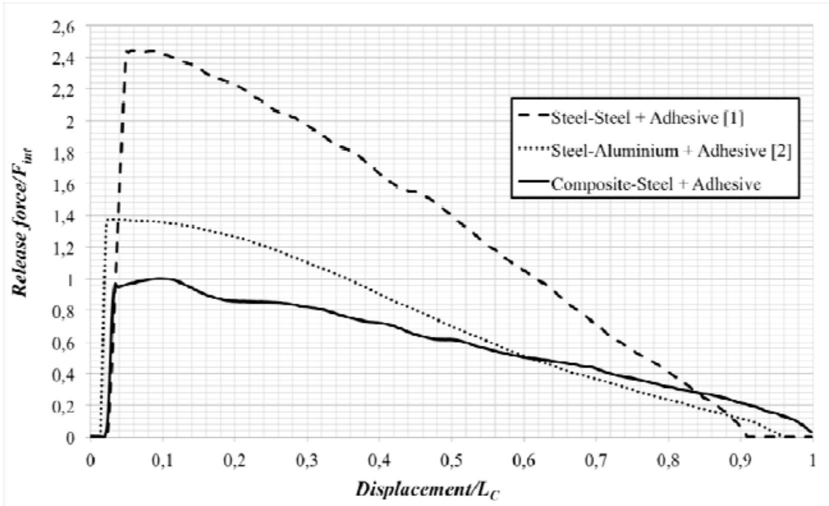
D. Croccolo, M. De Agostinis, S. Fini, G. Olmi, ” Influence of the engagement ratio on the shear strength of an epoxy adhesive by push-out tests on pin-and-collar joints: Parts I &II”, *International Journal of Adhesion & Adhesives, 67(2016): 69-75 & 76-85*

MOTIVATIONS

Two-component Epoxy adhesive is much more suitable for couplings between composite materials and metal.

Polymerizes in presence of oxygen

Makes it possible to join different materials without altering their structure



MOTIVATIONS

Possibility of bonding coatings for simple repair tasks: applications in aeronautics and in oil & gas

More efficient couplings in steering arms in automotive

Is there an engagement ratio (ER) dependence on push-out strength?

A big tank being repaired

MATERIALS AND METHODS

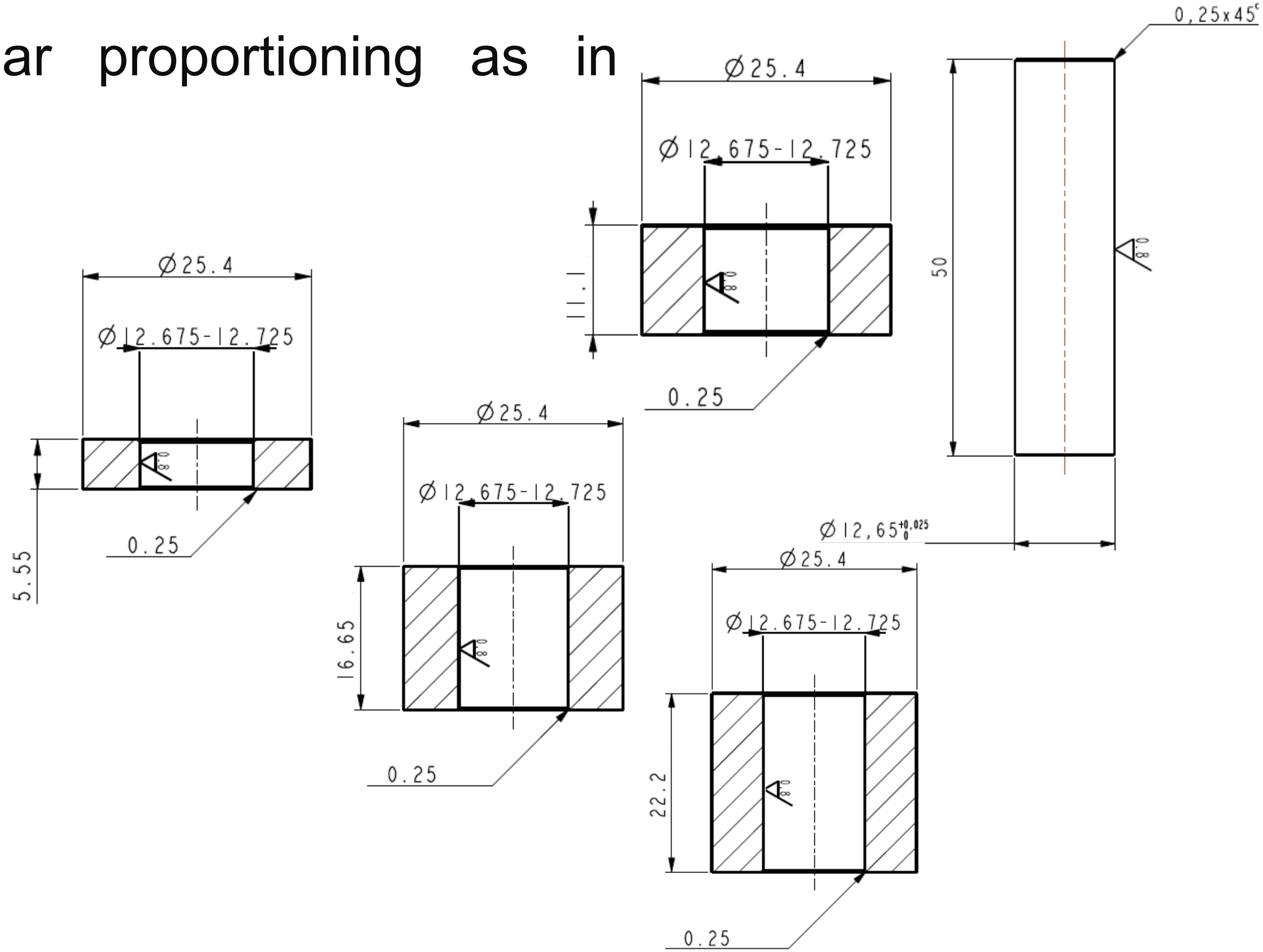
Pin-and-collar proportioning as in ISO 10123

ER=0.8

ER=0.4

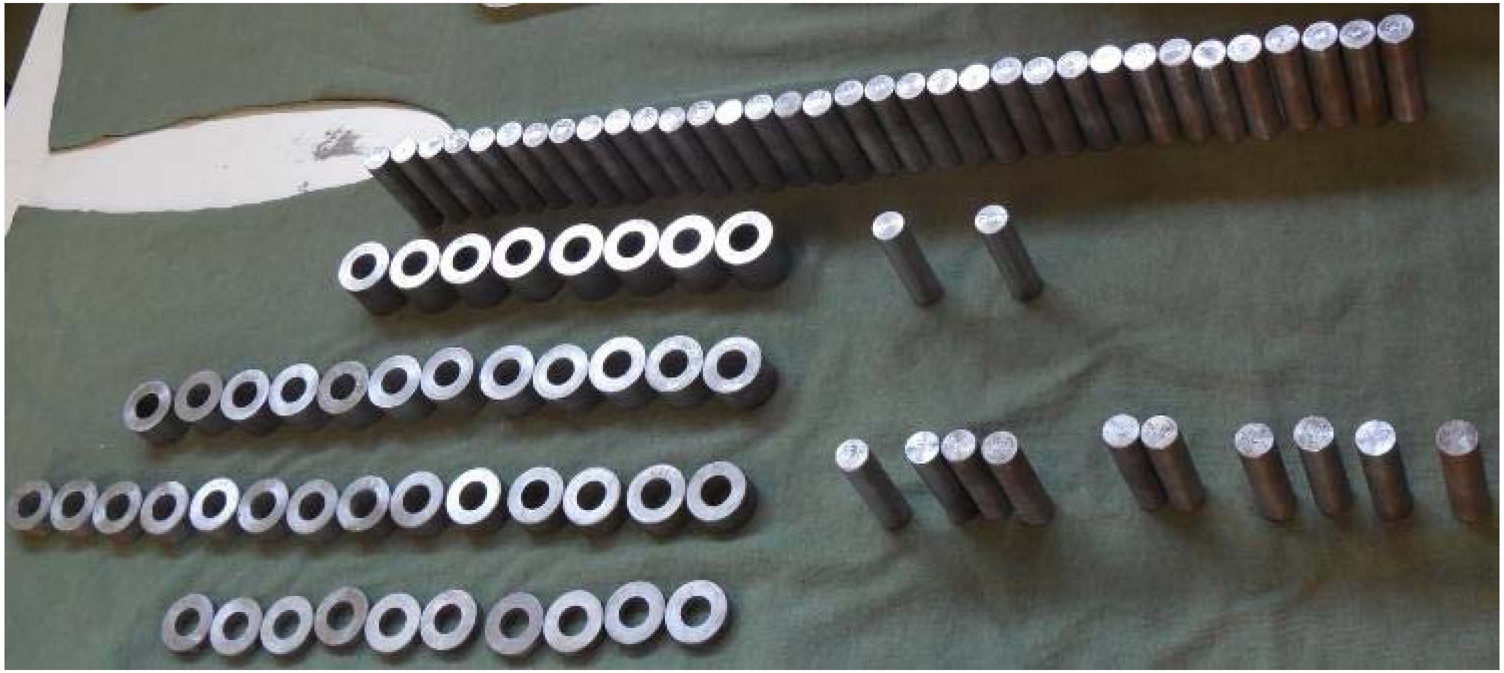
ER=1.3

ER=1.7



EXP. PROCEDURE

LOCTITE
7200



EXP. PROCEDURE

LOCTITE
9466

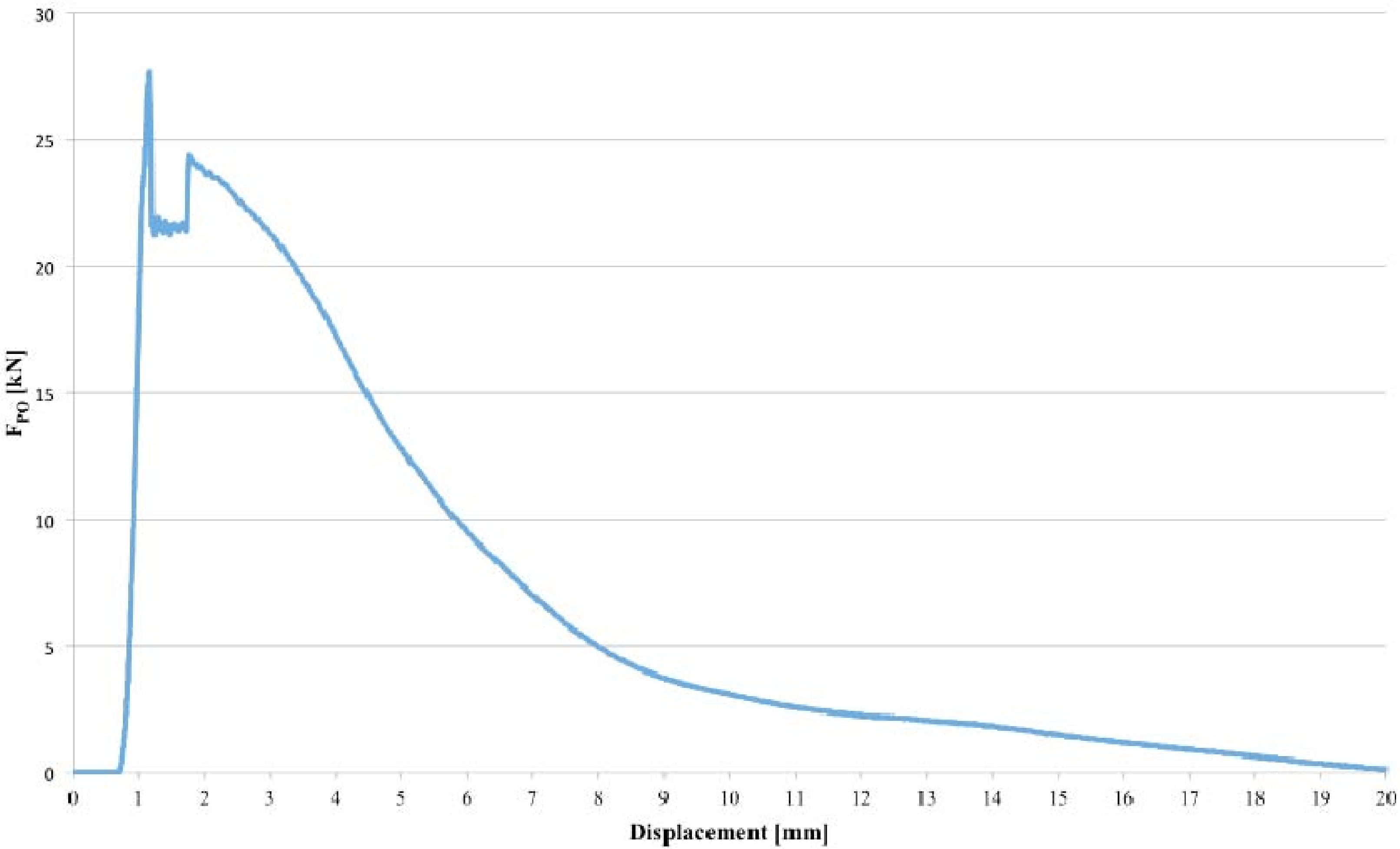
EXP. PROCEDURE

- 10 replications ER=0.4
- 10 replications ER=0.8
- 10 replications ER=1.3
- 10 replications ER=1.7
- Randomization

EXP. PROCEDURE

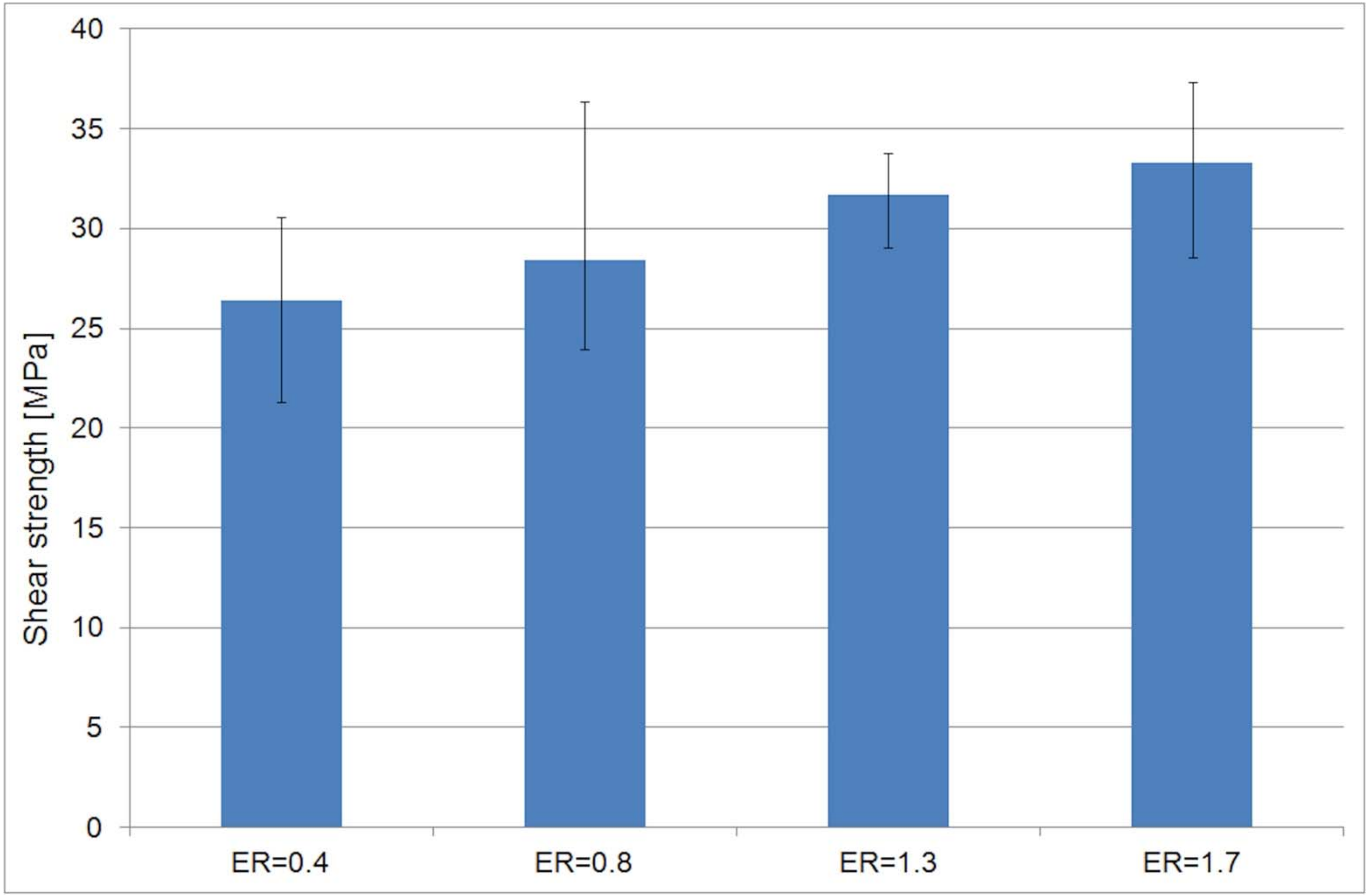
- The surfaces were cleaned by the LOCTITE 7200 cleaner and by a fine sandpaper
- The adhesive was prepared by mixing the two components with the special tool provided by the LOCTITE for 15 seconds
- The glue was spread on the specimen surfaces (the inner surface of collar, the outer surface of pin)
- The adhesive was cured for seven days at room temperature
- The pins were pushed out by means of the standing press machine with speed rate 0.03 mm/sec
- Two different loading cells (25kN and 250kN) applied to the superior clamp, depending on the different pushing out forces

RESULTS



30
25
20
15
10
5
0
F_{PO} [kN]
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Displacement [mm]

RESULTS



DISCUSSION

One-Factor ANOVA

SSQ		DoF	MSQ		$F_{calc.}$	p-$v.$
$SSBC$	291.72	3	$MSBC$	97.24	12.68	$8.28 \cdot 10^{-6}$
SSW	276.10	36	MSW	7.67		
TSS	567.82	39				

$$SSBC = R \cdot \sum_{j=1}^{C} \left(\bar{y}_{.j} - \bar{y}_{..}\right)^2 \qquad SSW = \sum_{j=1}^{C} \left[\sum_{i=1}^{R} \left(y_{ij} - \bar{y}_{.j}\right)^2 \right]$$

Differences are significant in this case

Refinement needed to allocate differences

DISCUSSION

Fisher's Least Significance Difference (LSD) Test

$$LSD = t \cdot \sqrt{MSW} \cdot \sqrt{\frac{2}{R}}$$

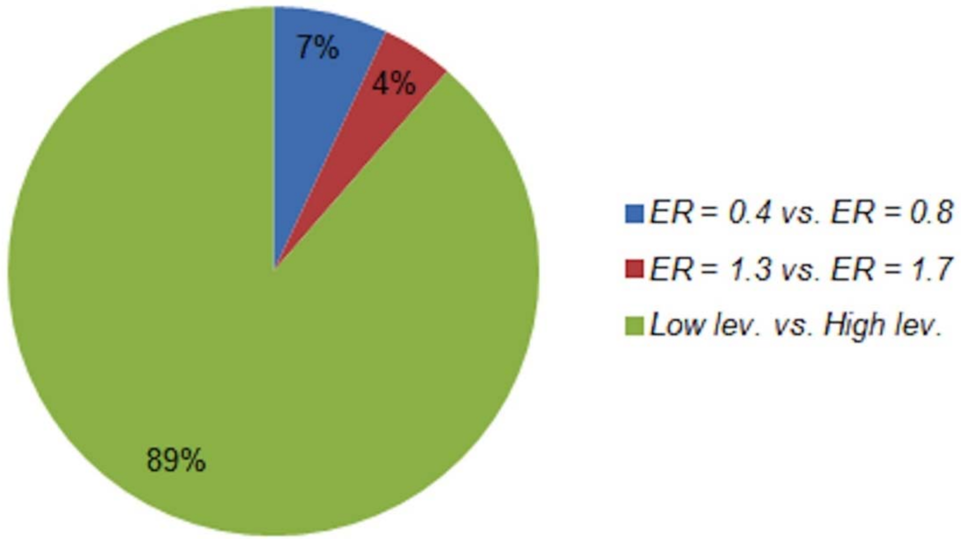
Test	Difference between means	*LSD* (Threshold)
$ER = 0.4$ vs. $ER = 0.8$	$\bar{y}_{.2} - \bar{y}_{.1} = 2.02$	
$ER = 0.8$ vs. $ER = 1.3$	$\bar{y}_{.3} - \bar{y}_{.2} = 3.27$	2.51
$ER = 1.3$ vs. $ER = 1.7$	$\bar{y}_{.4} - \bar{y}_{.3} = 1.60$	

DISCUSSION

Orthogonality and augmented ANOVA

SSQ		DoF	MSQ	$F_{calc.}$	p-v.
$SSBC$	291.72	3			
$ER = 0.4$ vs. $ER = 0.8$	*20.38*	*1*	*20.38*	*2.66*	11.18%
$ER = 1.3$ vs. $ER = 1.7$	*12.85*	*1*	*12.85*	*1.68*	20.38%
Low levels vs. *High levels*	*258.50*	*1*	*258.50*	*33.70*	$1.26 \cdot 10^{-6}$
SSW	276.10	36	7.67		
TSS	567.82	39			

SSBC split into three sources of variation



DISCUSSION

Orthogonality:

DoF of SSB_C = 3: 3 questions may be tackled

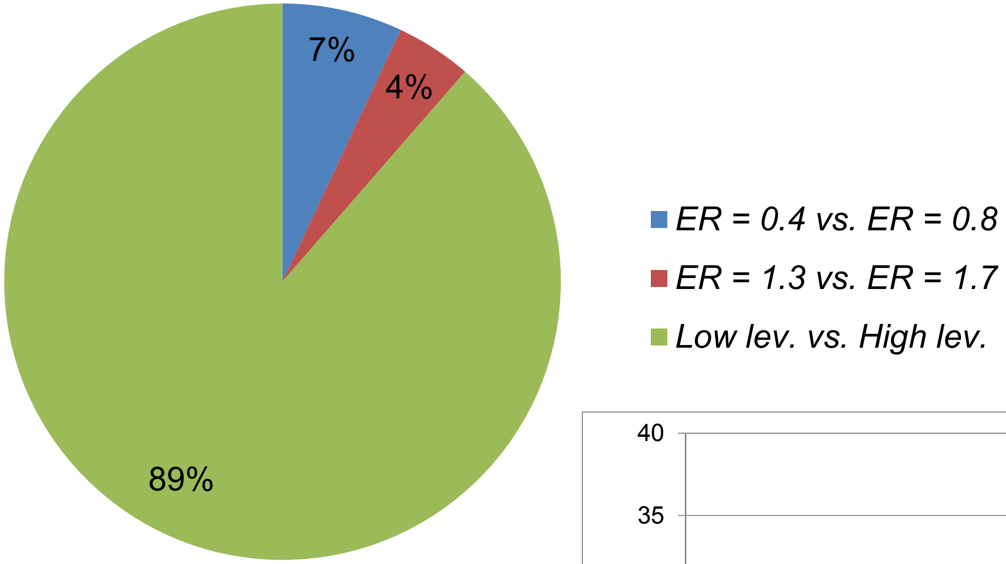
1) Significant differences between level ER=0.4 and level ER=0.8?
2) Significant differences between level ER=1.3 and level ER=1.7?
3) (If the aforementioned differences are not significant), are there significant differences between the low levels (taken altogether) and the high ones?

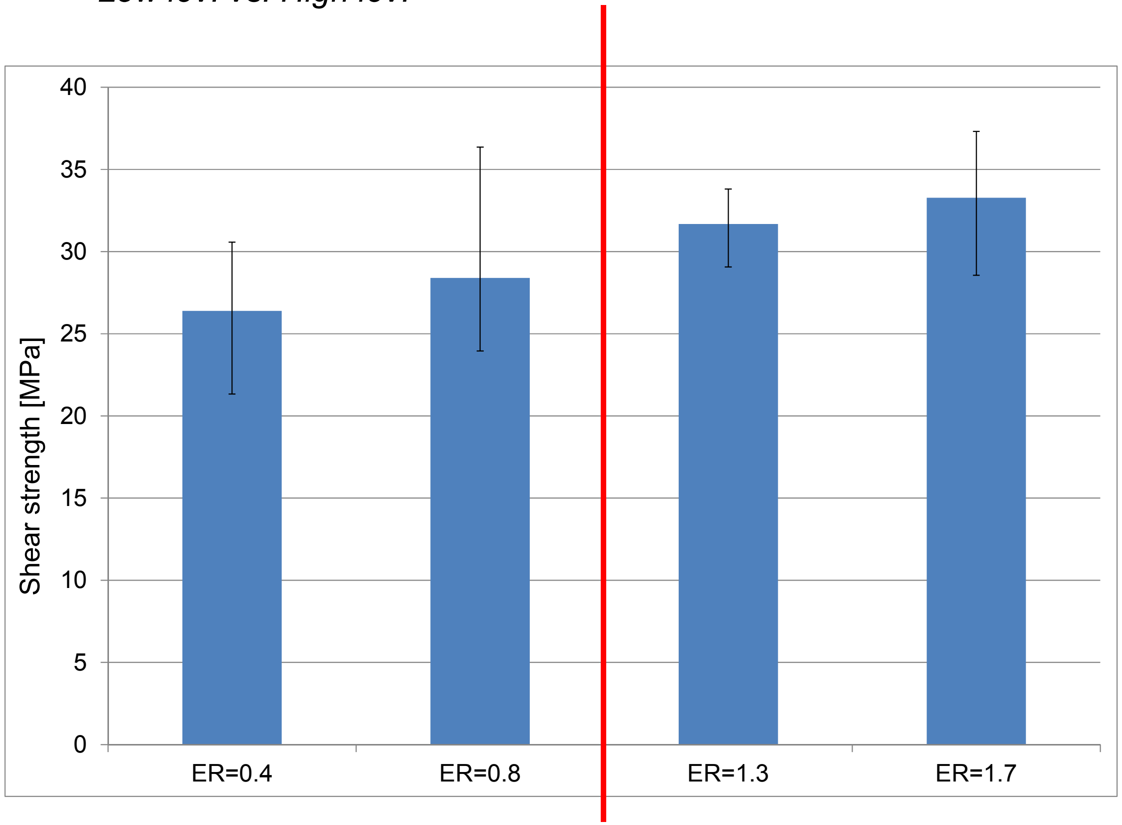
AUGMENTED ANOVA

	SSQ	GdL	MSQ	$F_{calc.}$	p-v.
SSB_C	291.72	3			
SSQ_1	20.38	1	20.38	2.66	11.18%
SSQ_2	12.84	1	12.84	1.67	20.39%
SSQ_3	258.5	1	258.5	33.70	$1.26 \cdot 10^{-6}$
SSW_C	276.10	36	7.67		
TSS	567.82	39			

The results of the LSD Tests are confirmed. Significant differences between the low and the high levels of ER. Shear strength significantly incremented for ER>=1.

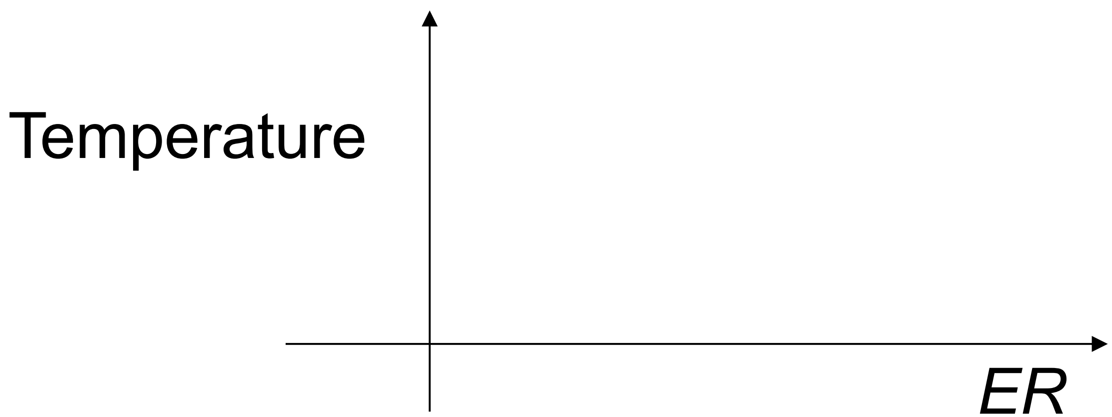
OUTCOMES


7%
4%
89%
ER = 0.4 vs. ER = 0.8
ER = 1.3 vs. ER = 1.7
Low lev. vs. High lev.


Shear strength [MPa]
0
5
10
15
20
25
30
35
40
ER=0.4
ER=0.8
ER=1.3
ER=1.7

TEMPERATURE EFFECT

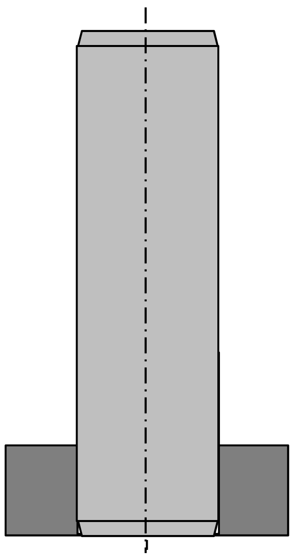
- The ER significantly affects the joint shear strength
- Studies regarding the effect of temperature and *ER* **in combination** are missing
- Combined study important to investigate interaction between the two factors



MATERIALS AND METHODS

Same samples as before

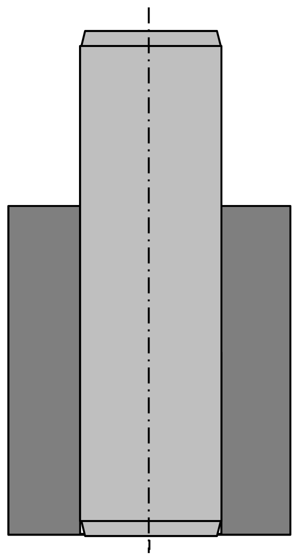
- Steel C40 UNI EN 10083-2
- Adhesive: LOCTITE 9466
- Specimen proportioning as in ISO 10123 and ASTM D4562-01



ER=0.4 to *ER*=1.7

4 levels for *ER*: 0.4; 0.8; 1.3; 1.7

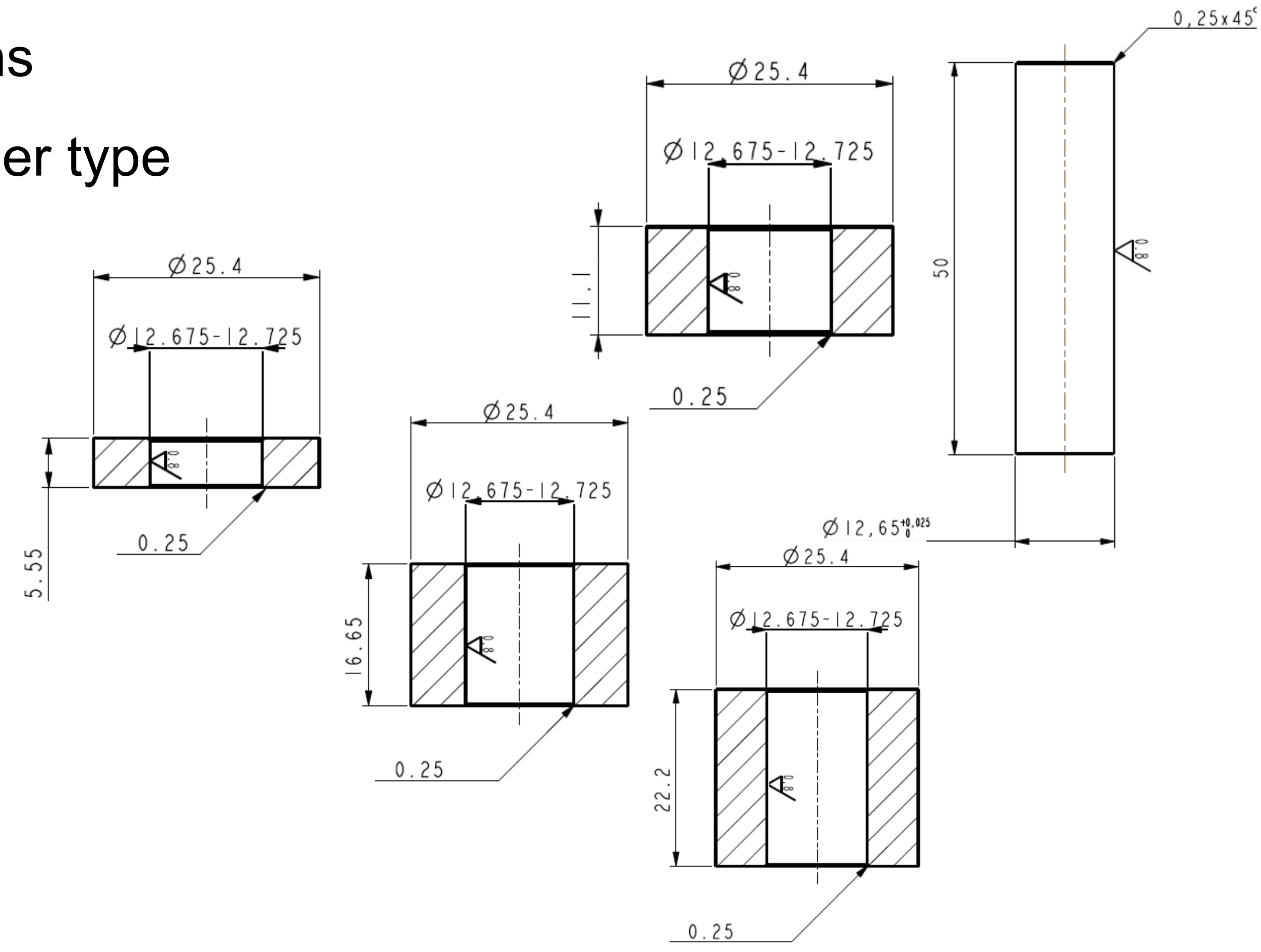
One half | Standard | Double



MATERIALS AND METHODS

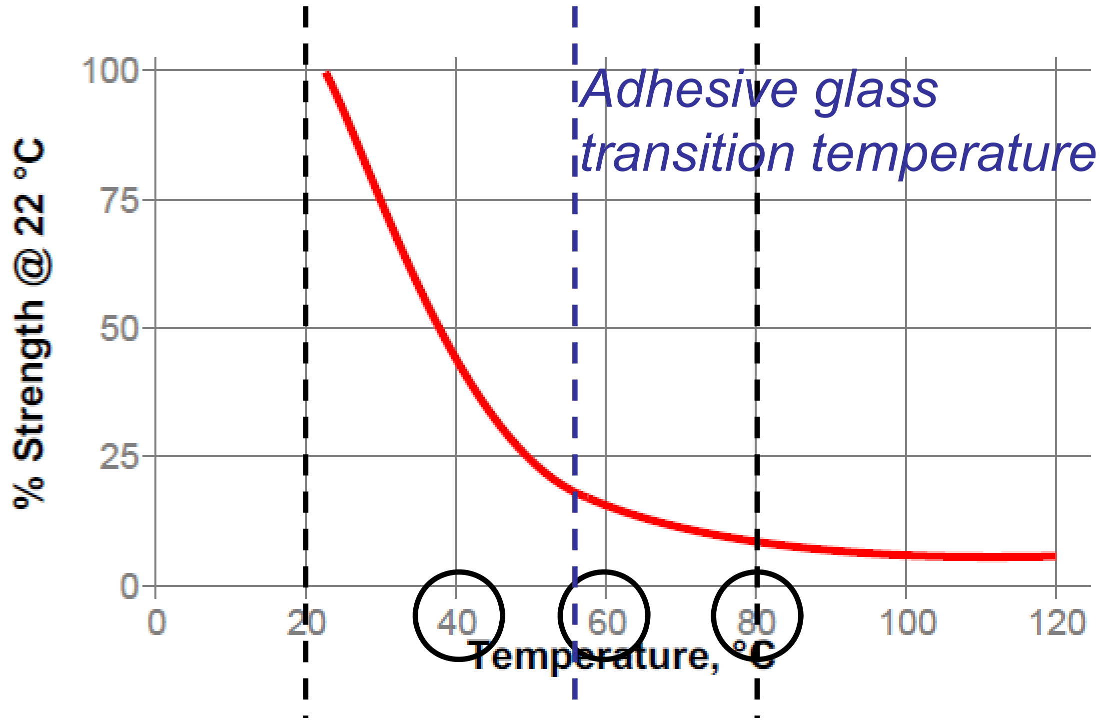
40 pins

10 collars per type



EXP. PROCEDURE

- Investigated temperature range: up to 80°C (low mechanical properties beyond 80°C)



- Tests at 40°C, 60°C, 80°C (uniform spacing)

EXP. PROCEDURE

- Campaigns at three temperature levels
- Four *ER* levels (0.4; 0.8; 1.3; 1.7)
- Ten replications

- Test order fully randomized

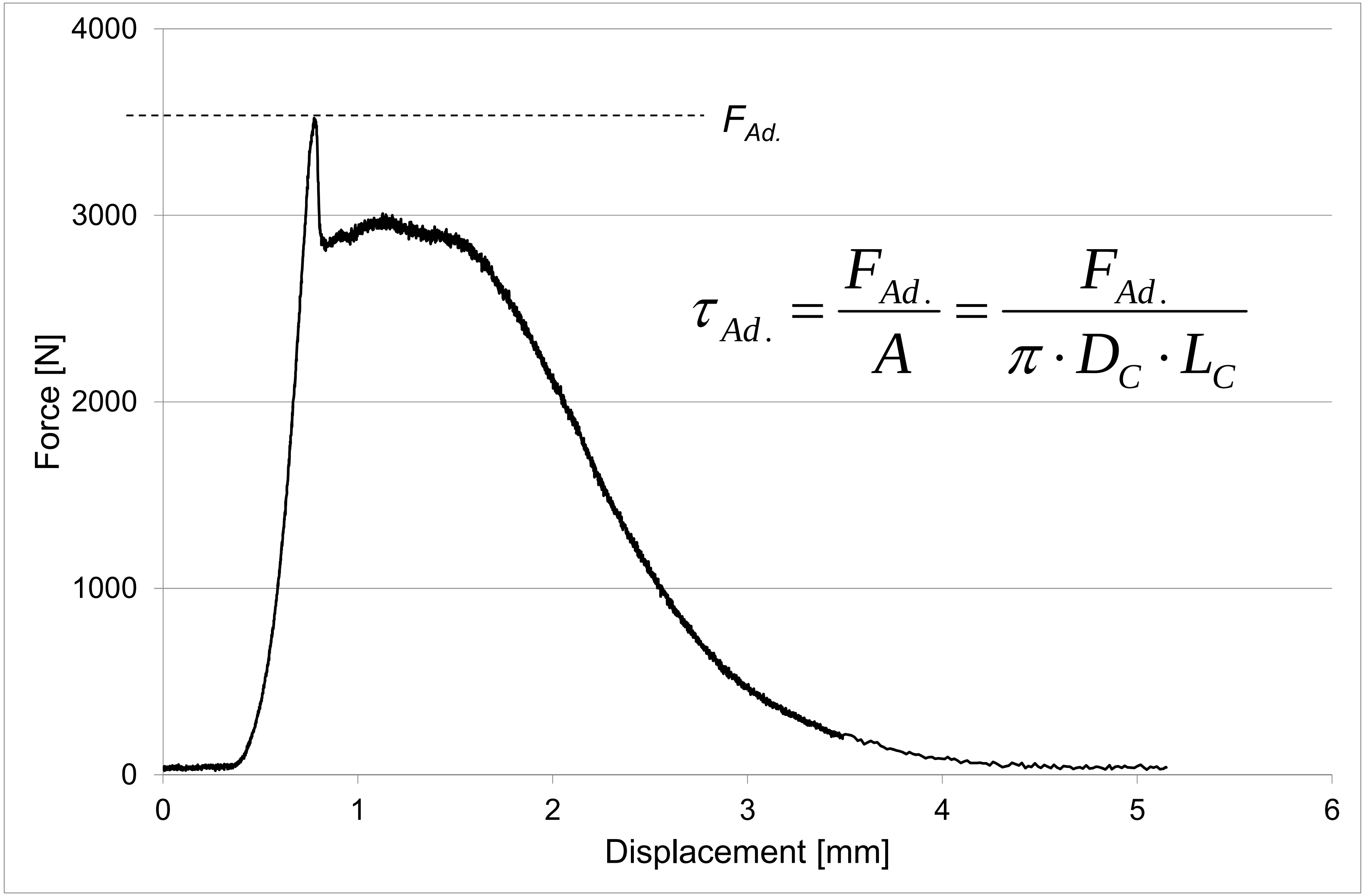
EXP. PROCEDURE

- Oven used to increase temperature, samples inserted upon steady-state temperature, maintained for 24 h
- Different randomized orders for coupling and decoupling

EXP. PROCEDURE

- Tests on a standing press with two load cells in series (capacities: 25 kN and 250 kN)
- Displacement controlled condition: ramp rate: 0.03 mm/s
- Recording of displacement and pushing-out force (sampling rate: 30Hz)

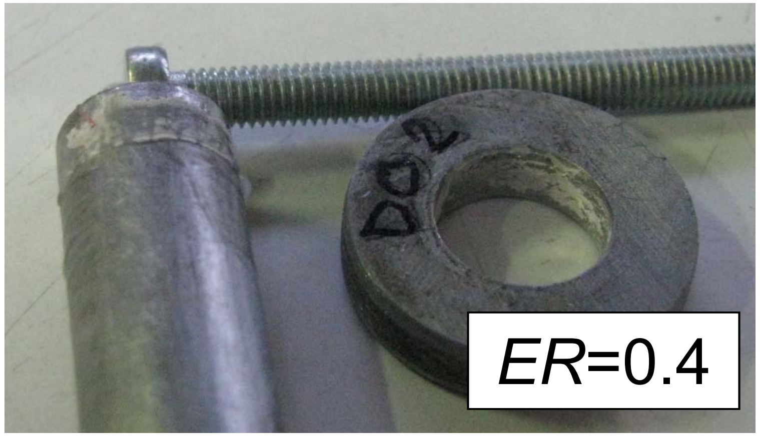
RESULTS

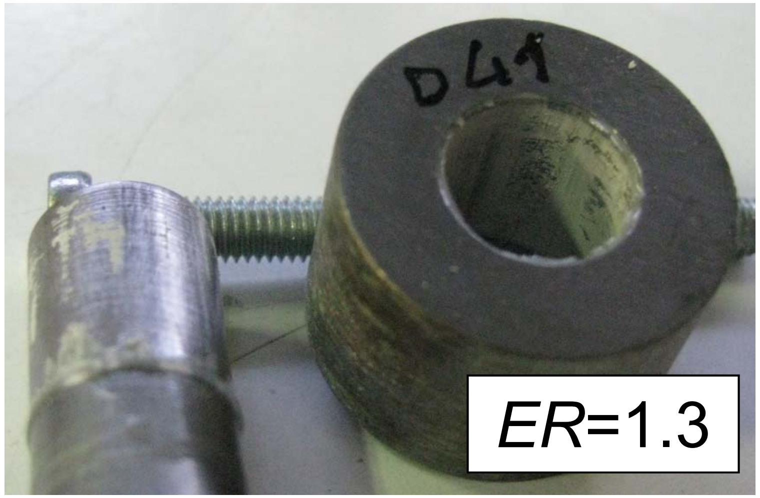


$$\tau_{Ad.} = \frac{F_{Ad.}}{A} = \frac{F_{Ad.}}{\pi \cdot D_C \cdot L_C}$$

RESULTS

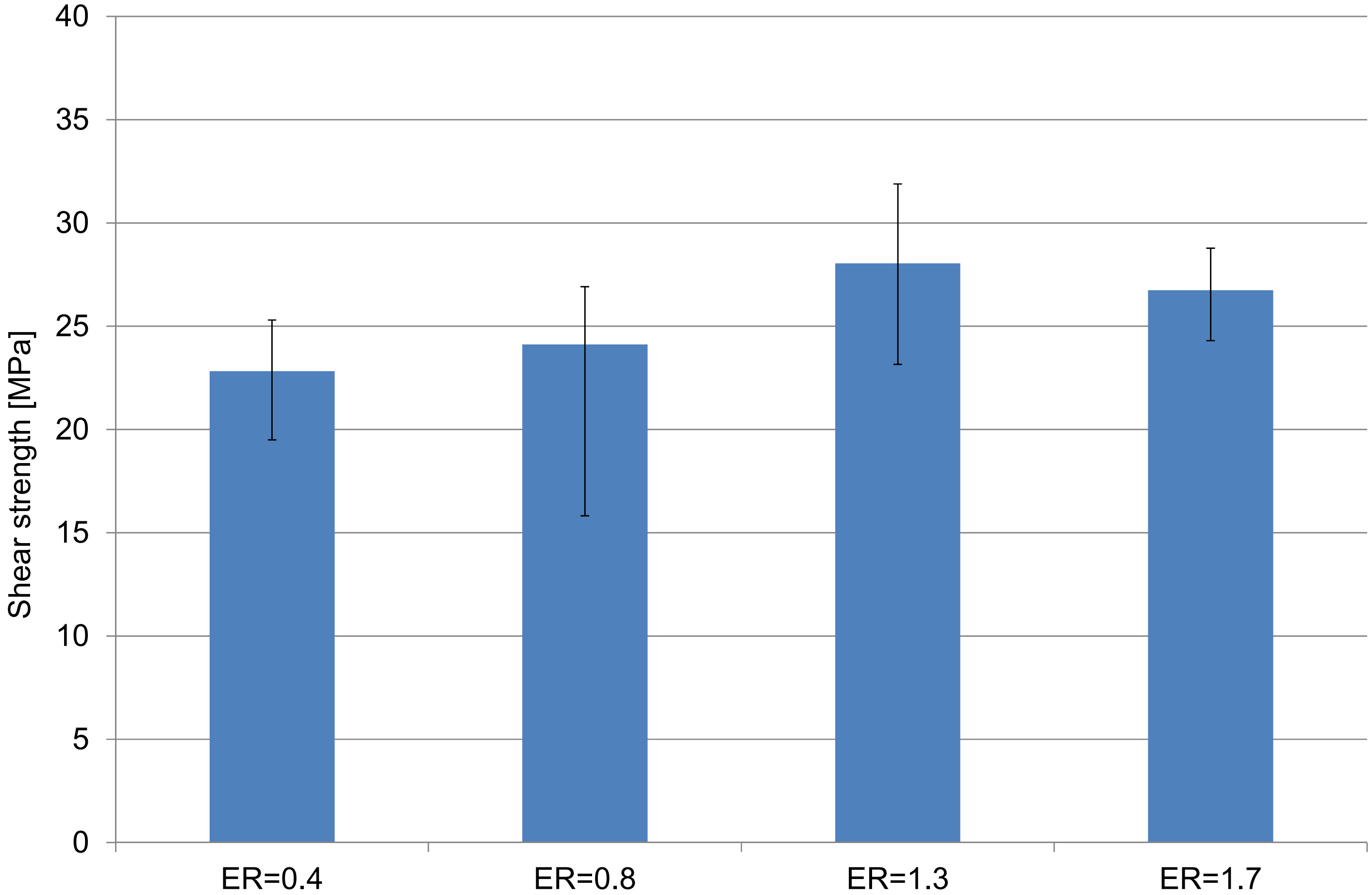
N.	Pin Diameter [mm]	Collar Diameter [mm]	Collar Length [mm]	Clearance [mm]	ER [-]	A [mm^2]	$F_{Ad.}$ [kN]
1	12.65	12.70	5.63	0.05	0.44	224.2	4.1
2	12.65	12.70	16.70	0.05	1.31	665.0	14.3
3	12.64	12.67	22.25	0.03	1.76	884.6	15.3
4	12.66	12.73	5.58	0.07	0.44	222.5	4.0
5	12.67	12.74	22.20	0.07	1.74	886.1	15.5
6	12.66	12.72	11.16	0.06	0.88	444.9	7.4
7	12.66	12.73	11.08	0.07	0.87	441.9	7.0
8	12.65	12.70	16.67	0.05	1.31	663.8	11.3
9	12.66	12.72	11.10	0.06	0.87	442.5	7.9
10	12.64	12.68	22.24	0.04	1.75	884.5	15.6
11	12.66	12.71	11.10	0.05	0.87	442.3	8.2
12	12.64	12.67	16.69	0.03	1.32	663.5	10.3
13	12.66	12.73	22.21	0.07	1.74	885.8	18.5
14	12.64	12.69	5.63	0.05	0.44	224.0	3.5
15	12.66	12.72	5.59	0.06	0.44	222.9	3.0
16	12.64	12.68	16.67	0.04	1.31	663.0	12.6
17	12.65	12.71	5.65	0.06	0.44	225.1	3.7
18	12.66	12.73	22.24	0.07	1.75	887.0	15.1
19	12.65	12.69	16.70	0.04	1.32	664.7	12.1
20	12.66	12.72	11.11	0.06	0.87	442.9	7.0
21	12.65	12.71	11.14	0.06	0.88	443.8	8.3
22	12.65	12.70	11.09	0.05	0.87	441.6	7.4
23	12.66	12.72	5.57	0.06	0.44	222.1	3.8
24	12.67	12.75	22.22	0.08	1.74	887.2	15.3
25	12.66	12.72	5.65	0.06	0.44	225.2	3.7
26	12.66	12.72	5.59	0.06	0.44	222.9	2.5
27	12.64	12.68	22.24	0.04	1.75	884.5	15.7
28	12.66	12.73	16.65	0.07	1.31	664.0	10.4
29	12.66	12.72	5.62	0.06	0.44	224.1	3.2
30	12.66	12.72	11.10	0.06	0.87	442.5	6.0
31	12.64	12.69	16.66	0.05	1.31	662.9	11.0
32	12.68	12.78	16.77	0.10	1.31	670.7	11.9
33	12.66	12.73	11.07	0.07	0.87	441.5	6.6
34	12.66	12.72	16.71	0.06	1.31	666.2	11.6
35	12.64	12.67	22.21	0.03	1.75	883.0	13.8
36	12.66	12.73	11.09	0.07	0.87	442.3	7.3
37	12.64	12.67	16.70	0.03	1.32	663.9	11.2
38	12.64	12.68	22.25	0.04	1.75	884.9	15.2
39	12.64	12.67	22.23	0.03	1.75	883.8	11.4
40	12.66	12.72	5.60	0.06	0.44	223.3	3.8





DISCUSSION

- Results at different temperature levels analysed first



t=40°C

DISCUSSION

- One-factor ANOVA

SSQ		*DoF*	*MSQ*	$F_{calc.}$	*p-v.*
SSBC	170.17	3	56.7	10.3	$5 \cdot 10^{-5}$
SSW	199.09	36	5.5		
TSS	369.26	39			

$$SSBC = R \cdot \sum_{j=1}^{C} \left(\overline{y}_{.j} - \overline{y}_{..} \right)^2$$

$$SSW = \sum_{j=1}^{C} \left[\sum_{i=1}^{R} \left(\overline{y}_{ij} - \overline{y}_{.j} \right)^2 \right]$$

ER significant

Prob. of error:
5/100.000

DISCUSSION

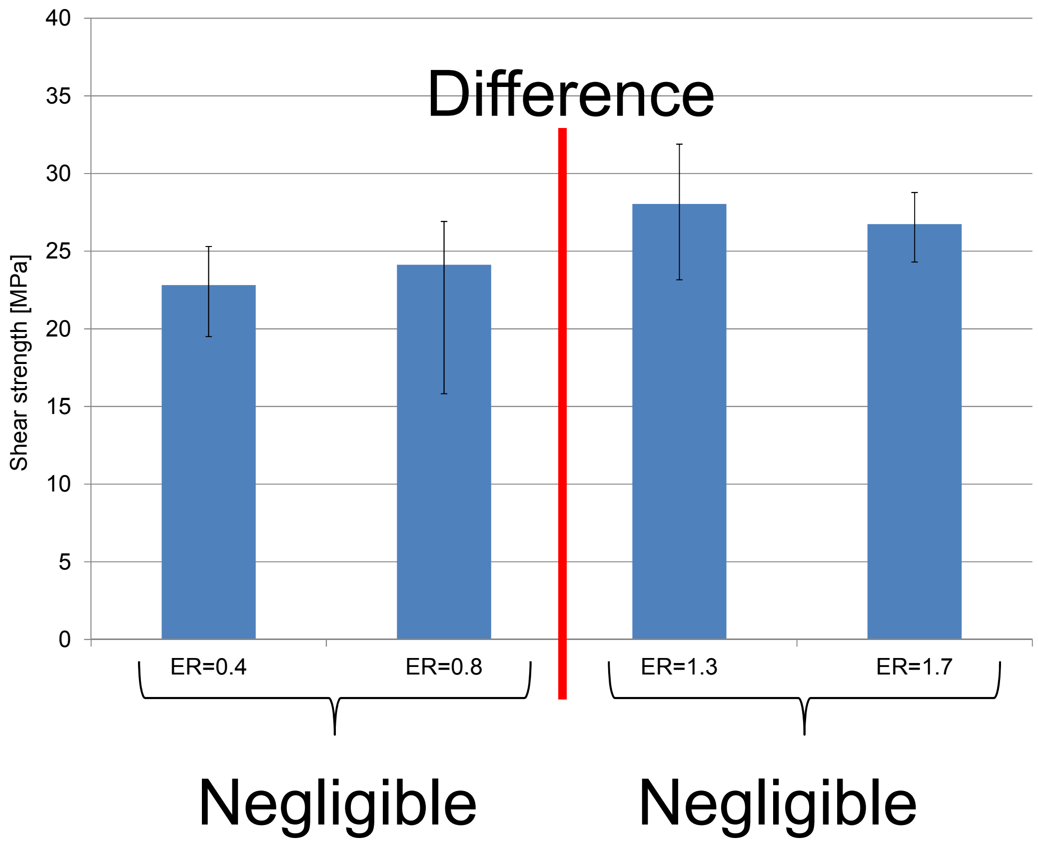
- LSD and Orthogonality

$$LSD = t \cdot \sqrt{MSW} \cdot \sqrt{\frac{2}{R}} = 2.13$$

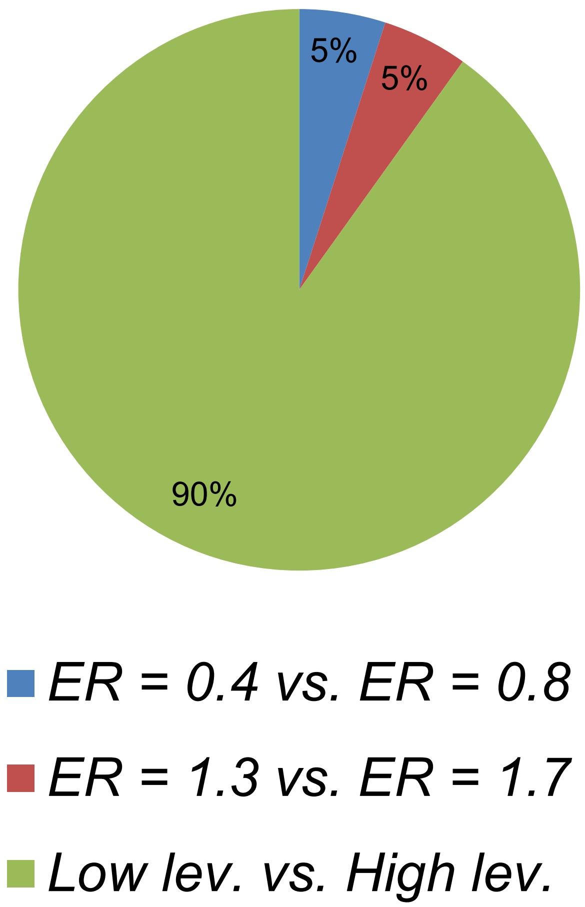
Significant difference between Low levels and High levels of *ER*

	SSQ	*DoF*	*MSQ*	$F_{calc.}$	*p-v*
SSBC	170.17	3			
0.4 vs. 0.8	*8.44*	*1*	*8.4*	*1.5*	*22.5%*
1.3 vs. 1.7	*8.40*	*1*	*8.4*	*1.5*	*22.6%*
Low lev.s vs. High lev.s	*153.33*	*1*	*153.3*	*27.7*	$7 \cdot 10^{-6}$
SSW	199.09	36	5.5		
TSS	369.26	39			

DISCUSSION



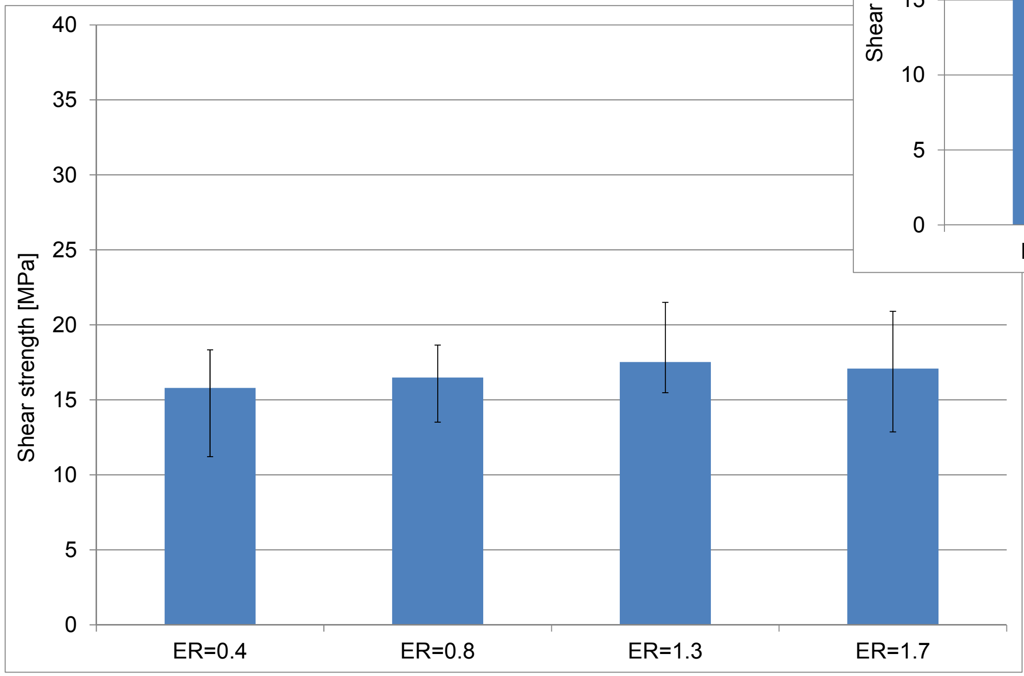
Shear strength [MPa]
40
35
30
25
20
15
10
5
0
Difference
ER=0.4
ER=0.8
ER=1.3
ER=1.7
Negligible
Negligible

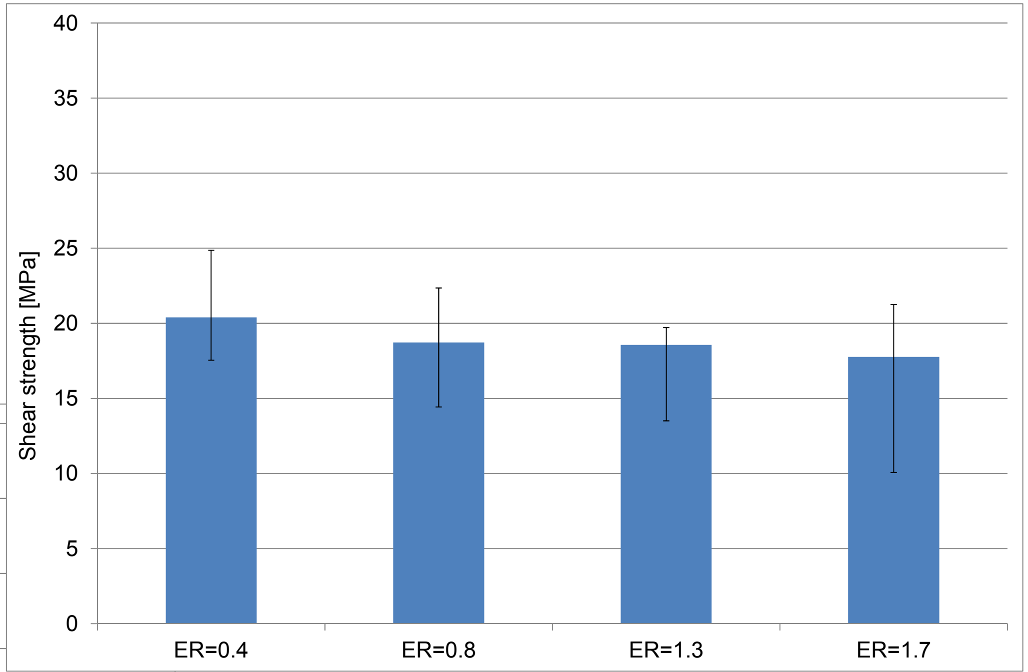


5%
5%
90%
ER = 0.4 vs. ER = 0.8
ER = 1.3 vs. ER = 1.7
Low lev. vs. High lev.

DISCUSSION

Results at 60°C…





… and at 80°C

DISCUSSION

- One-factor ANOVA

SSQ		*DoF*	*MSQ*	$F_{calc.}$	*p-v.*
SSBC	36.61	3	12.2	2.1	11.9%
SSW	210.51	36	5.85		
TSS	247.12	39			

t=60°C

SSQ		*DoF*	*MSQ*	$F_{calc.}$	*p-v.*
SSBC	16.74	3	5.6	1.5	21.9%
SSW	129.80	36	3.6		
TSS	146.53	39			

t=80°C

Not significant differences

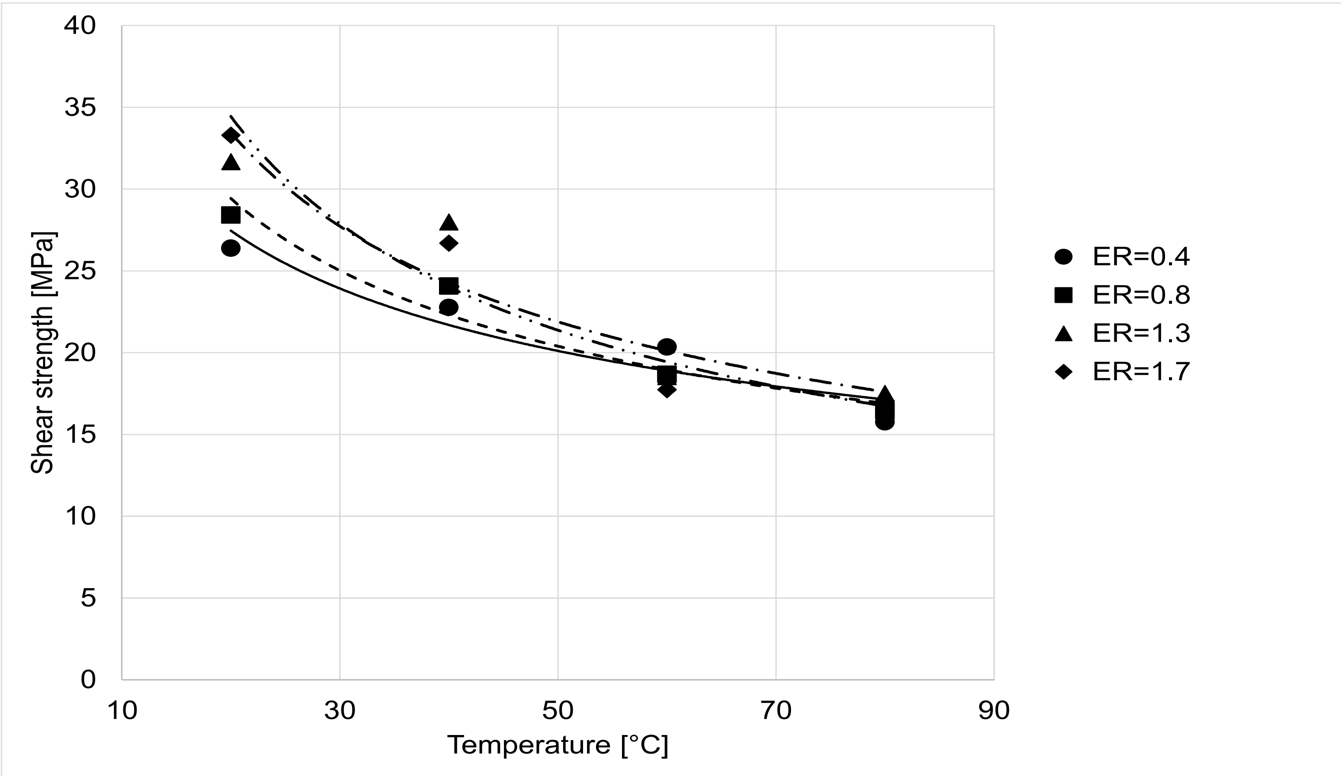
DISCUSSION

- At 40°C shear strength enhanced by increasing *ER*: recommended value: > 1, around 1.3, than saturation
- Consistent with results at room temperature

- Completely different behaviour at 60°C and 80°C → temperature threshold presumably related to the adhesive glass transition temperature

DISCUSSION

- Effect of *ER* decreasing for increasing temperature
- → Negative interaction
- Highly significant, according to two-factor ANOVA (p-v.=$2 \cdot 10^{-7}$)



THANKS FOR YOUR KIND ATTENTION

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