Investigating T-joint strength parameters using statistical experimental design and analysis techniques

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ABSTRACT: The strength of marine type T-joints has been investigated in a large experimental study using statistical experimental design methods to determine the effects of adhesive and surface cleaning. Statistical experimental design techniques proved invaluable in identifying, presenting and interpreting the significant interaction between the parameter effects. The solvent cleaned Crestomer joints were the strongest, and the dry cloth cleaned Crestomer joints were stronger than all other joints, whether the latter were solvent cleaned or not. The dry cloth cleaned polyester putty joints were the weakest, although the cloth-cleaned Crystic joints were only marginally stronger. The increase in joint strength achieved via cleaning with acetone and styrene monomer was much greater for the Crestomer joints than for the Crystic and polyester putty joints. There was not a great difference between the strengths of the Crystic and the polyester putty bonded joints.

1 INTRODUCTION

Composites have many advantages over traditional construction materials (such as resistance to the marine environment, ease of producing seamless multiple-curvature parts, and high specific strength) and are in fact themselves now ubiquitously used in the leisure craft industry (Shenoi et al. 2009).

However, a completed bare hull must be turned into the finished vessel through the addition of stiffeners, decks, superstructure, bulkheads & fittings, all of which must be joined together, requiring up to 50% of the total time & cost of build (Roland et al. 2004). Welding is obviously not an option for joining GRP, and mechanically fastening often induces stress concentrations.

Bonding is cheaper, lighter, needs significantly less assembly time, can join dissimilar materials and GRP, avoids hot work, does not change the base material properties, allows the use of thinner plating, can be performed from one side of the panel, and spreads the load over a greater area (Shenoi et al. 2009, Roland et al. 2004, Wang et al. 2003, Weitzenböck & McGeorge 2005). Flexible adhesives can also reduce vibrations, compensate for tolerance problems in large component assembly, accommodate thermal expansion differences and reduce stresses due to deformations (Roland et al. 2004, Wang et al. 2003, Cantril et al. 2005). Importantly in a marine context, bonding may also replace over-laminating to fix stiffeners to panels (Davies et al. 2004, Baur et al. 2004). Hence, adhesive bonding is a very attractive option.

However, the joining of these materials is very sensitive to many factors including the adhesives used, substrate preparation and adhesive application methods and conditions (Wang et al. 2003, Cantril et al. 2005). Surface preparation is especially critical in the marine industry given the generally less clean environment of a typical shipyard (Roland et al. 2004, Cantril et al. 2005). Two methods commonly used in the marine industry are simple mechanical grinding using hand-held ‘angle grinders’, and the use of a ‘peel ply’ where a textured polymer sheet is put on the uncured laminate and peeled off when cured (and preferably just before bonding is to be carried out) leaving a clean and textured substrate surface.

Additionally, the surface may be either simply cleaned with a clean, dry cloth, or better cleaned and then ‘activated’ (i.e. by breaking some of the long-string polymer bonds to allow improved secondary bonding) by wiping with acetone and then monostyrene solvents.

It is tempting to think that it is intuitive exactly how each of these parameters affects bond strength. However, in fact the effects of a given parameter may well vary depending on the value of other parameters; as a hypothetical example, ‘is the effect of surface activation the same for adhesive A as it is for adhesive B?’, or to state the same question in a more practical sense, ‘switching to adhesive B, will the surface still have to be activated?’

This type of problem is where statistically designed experimental techniques (Sutherland et al. 1998, Grove & Davies 1992, Box et al. 1978) become extremely useful, if not essential, to investigate such phenomena and then to analyse and present the results in a clear and interpretable manner. These methods provide a systematic approach to the planning and execution of the experimentation, and subsequent presentation, analysis and interpretation of the results obtained. Most importantly they are able to investigate any 'interactions' between parameters (such as in the hypothetical example given above) that occur.

A commonly used joint geometry for a large number of bonds found in the construction of a marine going vessel is the 'T'-joint, which is representative of many bonded structures including deck-hull, bulkhead-hull and deck-superstructure joints, amongst others.

Hence, an experimental study of the effects of a number of parameters commonly used in marine bonding on the strength of T-joints has been completed. The statistical and engineering interpretation of these results is ongoing, but initial results from a subset of the full test programme are presented and discussed in this paper.

2 EXPERIMENTAL DETAILS

All specimens were fabricated under typical shipyard conditions at Estaleiros Navais de Peniche, Portugal and then left for more than sufficient time for full cure to occur (in fact the specimens were in storage for over ten years before they were tested). The nominal dimensions of the T-joints are given in Figure 1.

Throughout this paper the vertical and horizontal sandwich laminates in the upper projection of Figure 1 are referred to as the 'base' and the 'web' of the T-joint, respectively. The Coremat sandwich laminate panels used to fabricate the base and web of the T-joints were hand laid-up with vacuum assistance using E-glass reinforced Scott Bader orthophthalic resin 446 PALV skins and a Lantor Coremat XM4 core.

The laminate schedule used was:

$$[600\,\mathrm{CSM},\ (300\,\mathrm{CSM},\ 800\,\mathrm{WR})_2,\ \mathrm{XM4}]_S$$

where: 300, 600 & 800 are areal weights in gm^{-2}, CSM is Chopped Strand Mat, WR is balanced Woven Roving, and XM4 is Coremat.

These sandwich laminates were then cut into a series of pairs of long strips which were bonded together at 90 degrees with fillets of adhesives applied using a radiused spatula. Individual specimens were then cut as 'slices' from this extended T-Joint.

As a suitably severe loading case the joints were supported and loaded as shown in Figure 2.

Specimen dimensions were measured and then a calibrated computer-controlled servo-hydraulic test machine was used to load the specimens at a controlled displacement rate of 0.1 mm/s until failure of the joint produced a significant and sudden drop in load. Force and displacement data was recorded and the strength of the joint taken as the maximum load achieved. Failure modes were also noted as the test progressed, and then verified using video recordings of each test.

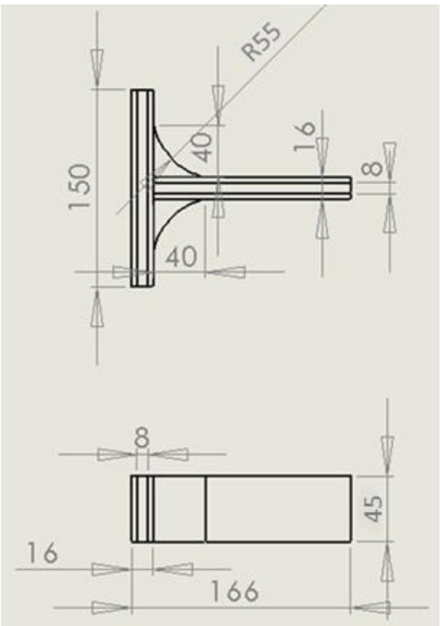

Figure 1. Nominal T-joint dimensions in mm.

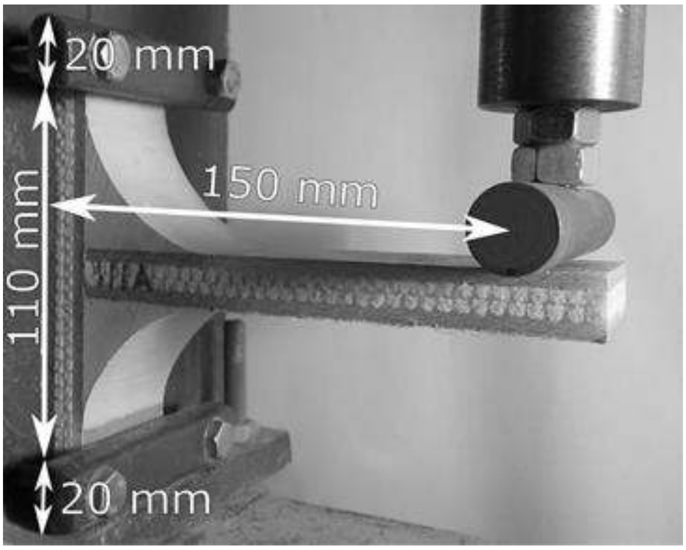

Figure 2. Test setup.

3 TEST PROGRAMME

Through consideration of common practice within the marine industry, the parameters and the values taken by each given in Table 1 were selected for study. In the language of designed experiments, 'parameters' and 'values' are referred to as 'factors' and 'factor levels' (or simply 'levels') respectively (Sutherland et al. 1998) and this terminology is used henceforth in this paper.

Surface preparation (PREP) consisted of no preparation ('None'), manual grinding ('Ground'), or the use of a peel-ply ('Peel'). Tests were performed for every combination of the various factor levels (i.e. 18), and each test was replicated 3 times, giving a total of 54 experimental results.

Table 1. Parameters and values

Factor	Level 1	Level 2	Level 3
Surface Preparation (PREP)	'None'	'Ground'	'Peel'
Adhesive (ADHES)	'Crest'	'Cryst'	'Poly'
'Cleaning' Method (CLEAN)	'Cloth'	'Solv'	-

Levels described in text.

However, as described in the introduction, only a subset of the full results is considered in the current paper, and this consists of the 18 experimental results with no surface preparation (i.e. PREP = 'None'). Hence, the surface preparation factor is not considered further here.

The three adhesives considered were:

i. **'Crest':** Scott Bader Crestomer 1186PA
ii. **'Cryst':** Scott Bader Crystic 2655PA (now '90-82PA')
iii. **'Poly':** A polyester putty of 25% mass content microfibers in Scott Bader orthophthalic 446 PALV resin.

The two 'cleaning' methods used were:

a) **'Cloth':** Simple wiping with a clean cloth
b) **'Solv':** Cleaning with acetone followed by surface activation with styrene monomer

4 RESULTS

The raw results obtained are given in Table 2. The maximum loads have been adjusted pro-rata for differences in the measured specimen widths from the nominal 45mm. Those specimens which were so weak to break upon cutting or handling were attributed a failure load of 0 kg.

A typical force-displacement plot and the four failure modes seen are shown in Figures 3 and 4 respectively.

5 STATISTICAL ANALYSIS

The open source, free statistical analysis software 'R' (R Core Team 2015) via the 'R-Studio' software (RStudio Team 2015) was used for the statistical analyses of the experimental data. Appropriate factor levels were assigned to the factor variables 'CLEAN' and 'ADHES', and measured experimental data assigned to the response variable 'MaxF'.

An estimated linear model of the maximum force response as described by the two factors and their interaction term was fitted to the data. A residual analysis to check the validity of the model and a summary of the model were completed. An analysis of variance (ANOVA) was then carried out.

Table 2. Experimental Results

Factor Levels		Maximum Load	Failure Mode*
CLEAN	ADHES	(kg)	
Cloth	Crest	78.3	BS
Cloth	Crest	67.4	BS
Cloth	Crest	73.5	BS
Cloth	Cryst	17.0	UB/LWS
Cloth	Cryst	9.6	UB/LWS
Cloth	Cryst	0.0	UB/LWS
Cloth	Poly	0.0	BS
Cloth	Poly	0.0	BS
Cloth	Poly	0.0	BS
Solv	Crest	132.5	UBD
Solv	Crest	127.0	UBD
Solv	Crest	133.5	UBD
Solv	Cryst	27.4	BS
Solv	Cryst	25.4	BS
Solv	Cryst	32.8	BS
Solv	Poly	18.8	UW/LBS
Solv	Poly	16.6	UW/LBS
Solv	Poly	29.5	UW/LBS

*B = Base, W = Web, U = Upper, L = Lower, S = Separation, D = Delamination

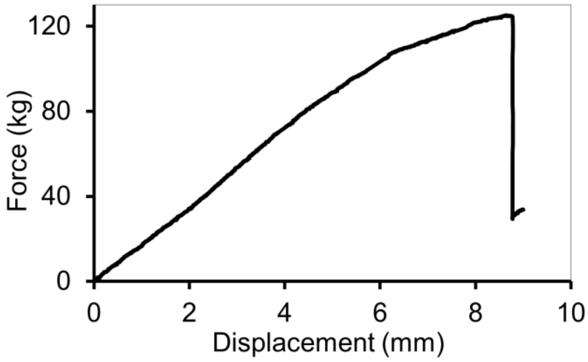

Figure 3. Typical force-displacement data.

The statistical model was shown to be extremely valid, with an 'R^2' value of 0.99 (a value of 1.0 indicates a perfect fit to the data) and Levene's tests and a normal Q-Q plot (Figure 5) of the residuals showed that the data was both homoscedastic (i.e. of homogeneous variance) and sufficiently normally distributed.

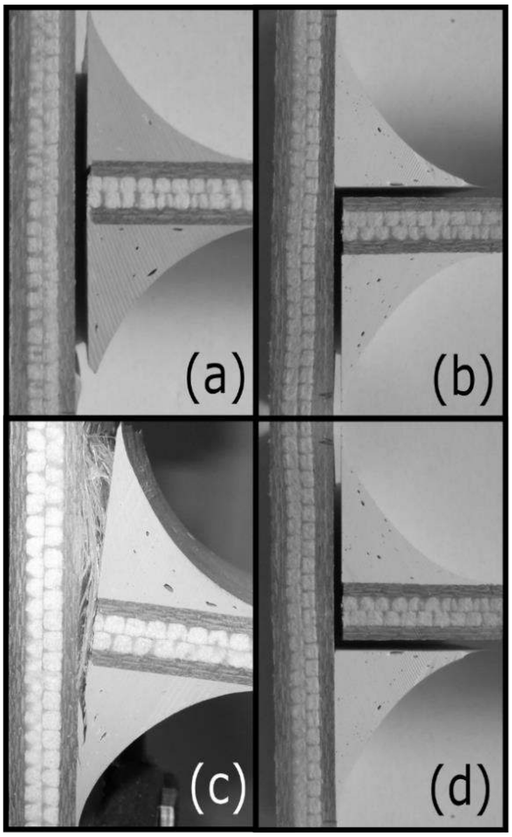

Figure 4. Failure modes: (a) Base Separation (BS), (b) Lower Base Upper Web Separation (LB/UWS), (c) Upper Base Delamination (UBS), (d) Upper Base Lower Web Separation (UB/LWS)

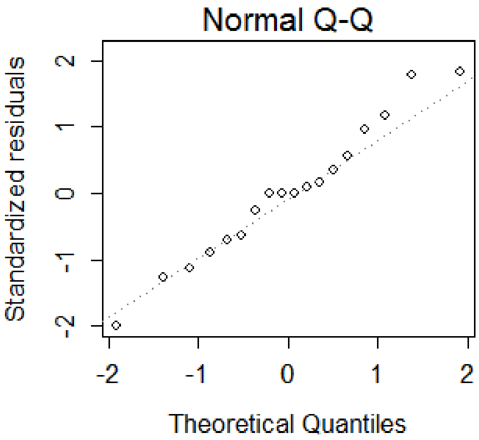

Figure 5. Normal Q-Q plot.

The ANOVA results in Table 3 show that both factors were extremely statistically significant (at a level of well under a 1 in a million chance that the effect seen is in fact not real but just due to statistical variation); i.e. it is extremely safe to assume that they are 'real effects'.

Table 3. ANOVA results (response: max. force)

Factor / Interaction	Pr(>F)
CLEAN	2.118e-08
ADHES	2.216e-12
CLEAN:ADHES	6.928e-05

It is worth noting here that just because an effect is statistically significant, or 'real', it does not have to mean that it is large enough in practical engineering terms to be of any interest; it is just large enough to be distinguished above the statistical 'noise' in the data. These effects are shown in Figure 6(a) and (d), but as explained below, in this case these 'main' effects and plots should not be taken on face value due to significant interaction effects.

Table 3 also shows that the interaction between the effects of adhesive and cleaning factors is extremely statistically significant. This means that the effects of one factor are different for the different levels of the other factor, and this type of interaction between two factors ('2-way interactions') is best illustrated using 'interaction plots' as given in Figure 6(b) and (c).

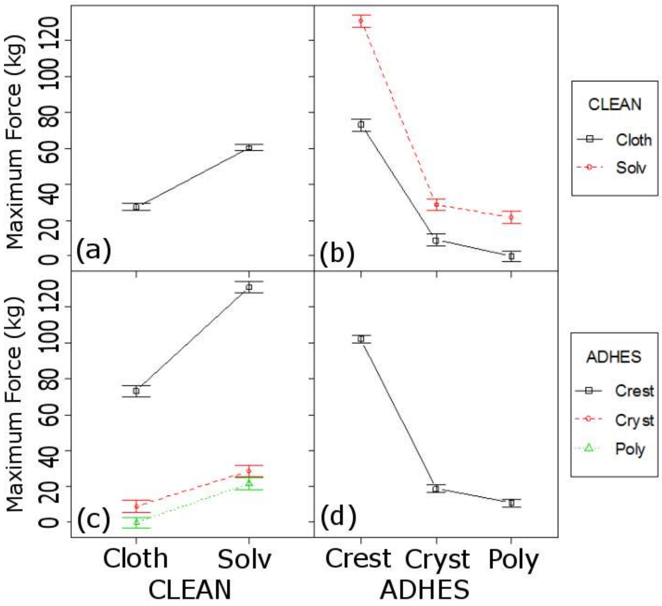

Figure 6. Factor Main and Interaction Effect Plots (SE bars).

Using Figure 6(c) to explain the interpretation of the interaction plots, this plot shows that the effect of changing the level of factor CLEAN from Cloth to Solve does not have the same effect on the response Maximum Force for all levels of factor ADHES; the effect of factor CLEAN is far greater for the Crestomer level of ADHES than it is for the Crystic and polyester putty levels. That is, an *interaction* exists between the effects of the main factors CLEAN and ADHES.

The main factor effect plots of Figures 6(a) and (d) are the *averaged* factor interaction plots of Figures 6(c) and (b). Hence, taking Figures 6(a) and (c) as an example, since Figure 6(c) shows a significant interaction between the factor effects then Figure 6(a) (which is an average of the effects seen in Figure 6(c)) is at best misleading, and should not be considered. Putting this another way, if the experiment was carried out varying the factor CLEAN only for Crestomer bonded T-joints, the results would lead to the conclusion that the cleaning method had a large effect on the joint strength. However, Figure 6(c) clearly shows that this effect is not as large for T-joints bonded with Crystic or polyester putty.

Hence, since the interaction effect here was seen to be extremely significant in Table 3, Figures 6(a) and (d) will not be further referred to in this paper.

This ability of statistically designed experimentation and analysis to systematically investigate, and, importantly, to clearly represent graphically, factor interactions is a very powerful tool, extremely useful (if not essential) in any situation where multiple parameters affect the measured response and interactions between the factor effects are possible. Many areas of research into composite materials fall into this multi-parametric category (e.g. Sutherland et al. 1998, Sutherland & Guedes Soares 2003).

6 DISCUSSION

6.1 *Engineering interpretation of statistical results*

This is the most important and useful part of the experimental design process. It is worth repeating that a statistically significant effect does not necessarily infer an important effect in practical terms; it may still be too small to be of any real importance.

It is also important to remember that in this paper all specimens received no surface preparation in the sense of grinding or use of peel ply.

Here the interaction effects between the CLEAN and ADHES factors will be discussed using Figures 6 (b) and (c). Inspection of these two figures will reveal that they are in fact two different plots of the same six data points. However, this does not mean that one is superfluous since they both give a slightly different practical interpretation of the same data.

Figure 6(c) shows that for either surface cleaning method (Cloth or Solv) the Crestomer adhesive produced a much stronger joint, and also that there was little difference in the strength of Crystic and polyester putty bonded joints. It also shows that cleaning with solvents increases the strength of the Crestomer joints by a larger amount than it does that of the Crystic and polyester putty bonded joints.

The weakest joints are seen to be those of polyester putty cleaned with a dry cloth, although whether the strength of the cloth-cleaned Crystic joints is statistically greater would require further analyses. In any case this difference is small in engineering terms. It also shows that, for this study of T-joints with unprepared surfaces for this test specific set-up, the use of Crystic is not beneficial in terms of joint strength over the use of cheaper polyester putty.

Finally, Figure 6 (c) clearly show that the strongest joint here is that made using a Crestomer adhesive cleaned with solvents before bonding.

The same conclusions made from Figure 6(c) discussed above, can also be made through inspection of Figure 6(b), although they are perhaps not so obvious. For example it can be seen from Figure 6(b) that the effect of cleaning with solvents over cleaning with a dry cloth has a greater effect for the Crestomer bonded joints than for the other two adhesives considered. However, Figure 6(b) does more clearly show the fact that Crestomer joints are the stronger joints in all cases, and that Crystic joints are slightly stronger than the equivalent polyester putty joints.

6.2 *Failure Modes*

In order to more clearly illustrate the link between the failure modes and the factor effects seen, Figure 7 shows the data points of Figure 6(b) annotated using the failure modes of Table 3.

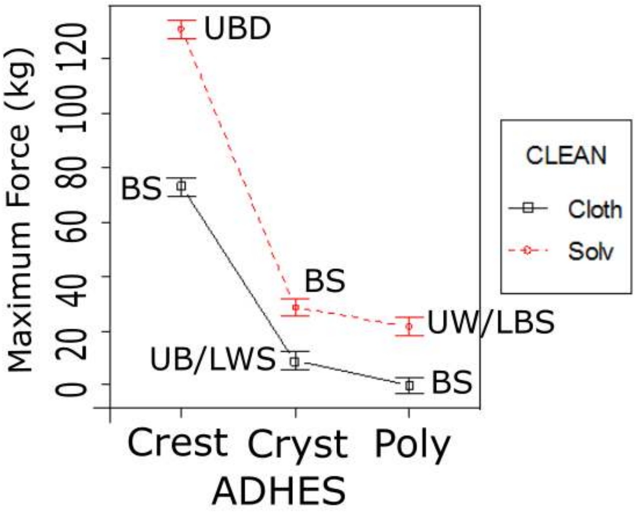

Figure 7. Factor interaction effects and failure modes

Figure 7 clearly shows that the strongest specimens, the solvent cleaned Crestomer joints, were also the only ones to fail with a delamination of the substrate laminate. This shows that the bond achieved in these joints was stronger than the interlaminate tensile strength of the GRP skins.

All of the other tests suffered some form of separation of the adhesive and substrate laminate, giving correspondingly weaker joints. The dry cloth cleaned specimens failed with upper base / lower web and base separations for Crystic and polyester putty bonded joints, respectively, although the error bars indicate that this is not a very statistically significant difference between the two strengths (also see Figure 6(c)), and this is certainly not a very significant difference when compared to the failure load of the strongest joints. Similarly, the solvent cleaned specimens failed with base and upper web / lower base separations for Crystic and polyester putty bonded joints, respectively, and again the error bars indicate that this is not a very statistically significant difference between the two strengths (also see Figure 6(c)). Again, this is certainly not a very significant difference when compared to the failure load of the strongest joints.

Hence, it can be inferred that the various geometries of the separation failure modes of the Crystic and polyester putty joints are not particularly correlated to joint strength.

The dry cloth cleaned Crestomer joints failed via separation of the base, but these joints were much stronger than all the other joints failing via separation. In fact, the strength of the bond of these dry cloth cleaned Crestomer joints is still considerably higher than that of any of the joints using either of the other two adhesives considered, even if the latter were cleaned using solvents.

7 CONCLUSIONS AND FURTHER WORK

The use of statistically designed and analysed experiments has been used to investigate the effects of various parameters on the strength of marine type T-joints. The full test programme considered effects of surface preparation, adhesive and surface cleaning, with this paper reporting initial findings of the latter two parameters only.

The statistical experimental design techniques proved invaluable in identifying, presenting and interpreting the interaction between the effects of the parameters. Simple statistical analyses were able to distinguish the parameter effects from the underlying statistical variation, or ‘error’. The statistical model used was found to represent the data very accurately.

The interaction between the effects of adhesive and cleaning factors was seen to be extremely statistically significant, i.e. the effect of one parameter was different depending on the value of the other parameter. This interaction between two parameters was clearly illustrated using ‘interaction plots’.

Conclusions concerning the strength of the T-joints tested (i.e. those without any surface preparation) include:

- The solvent cleaned Crestomer joints were the strongest joints by a large margin.
- The dry cloth cleaned Crestomer joints were stronger than all other joints, whether the latter were solvent cleaned or not.
- The dry cloth cleaned polyester putty joints were the weakest, although the cloth-cleaned Crystic joints were only marginally stronger.
- The increase in joint strength achieved via cleaning with acetone and styrene monomer was much greater for the Crestomer joints than for the Crystic and polyester putty joints.
- There was not a great difference between the strengths of the Crystic and the polyester putty bonded joints

Further work concerns the completion of the analysis of the full data set by including the third parameter of surface preparation, and of the more complex statistical analyses require to this end.

8 ACKNOWLEDGEMENTS

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