Effect of post-cure on adhesively bonded functionally graded joints by induction heating

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Abstract

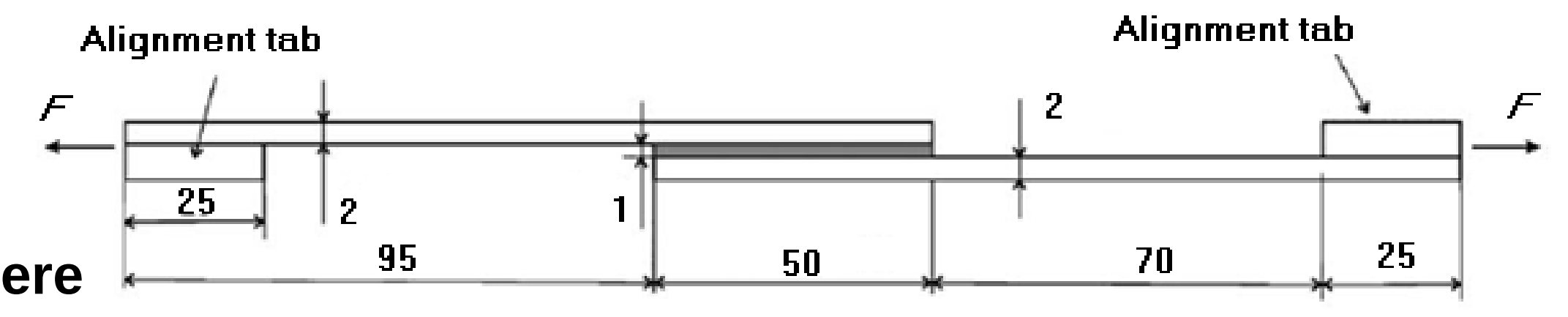
Functionally graded joints with an adhesive functionally modified by induction heating confer a more uniform stress distribution along the overlap and reduce the stress concentrations located at the ends of the overlap. The adhesive stiffness varies gradually along the overlap, being maximum in the middle and minimum at the ends of the overlap [1].
The effect of post-curing on functionally graded joints obtained by induction heating was studied in order to understand the performance of functionally graded joints when submitted to different post-cure temperatures. Three different post-curing conditions were considered, with temperatures above and below the glass transition temperature of the fully cured network, $T_{g\infty}$. The functionally graded joints (with and without post-cure) were compared with joints cured isothermally (with and without post-cure). The cure temperature values applied to the ends and to the middle of the graded joint are the same temperatures used to cure the isothermally cured joints. Analytical modelling to assist with the prediction and assessment of the possible effectiveness of a graded joint concept. The functionally graded joints subjected to post-cure at low temperatures (below $T_{g\infty}$) show a slight decrease of the strength and the joints cured isothermally show a slight increase of the strength. With increase of the post-cure temperature (above $T_{g\infty}$) the functionally graded joints exhibit strength similar to that of the joints cured isothermally. However, even for the highest post-cure temperatures, the functionally graded joints have a slightly higher strength.

Experimental details

Materials

The adhesives selected are two bi-component epoxy adhesives, Araldite® 2011 and Loctite Hysol® 3422, which mechanical properties were determined as a function of the cure temperature by Carbas *et al*. [2-3].

Single lap joint (SLJ) test



- Isothermal cure

Two different cures in a hot press were performed for each adhesive, one cure in order to achieve stiff, but strong brittle properties of the adhesive and another cure in order to obtain ductile properties of the adhesive.

- Graded cure

A new induction heating system was developed to allow a grade cure [4].

Post-cure conditions

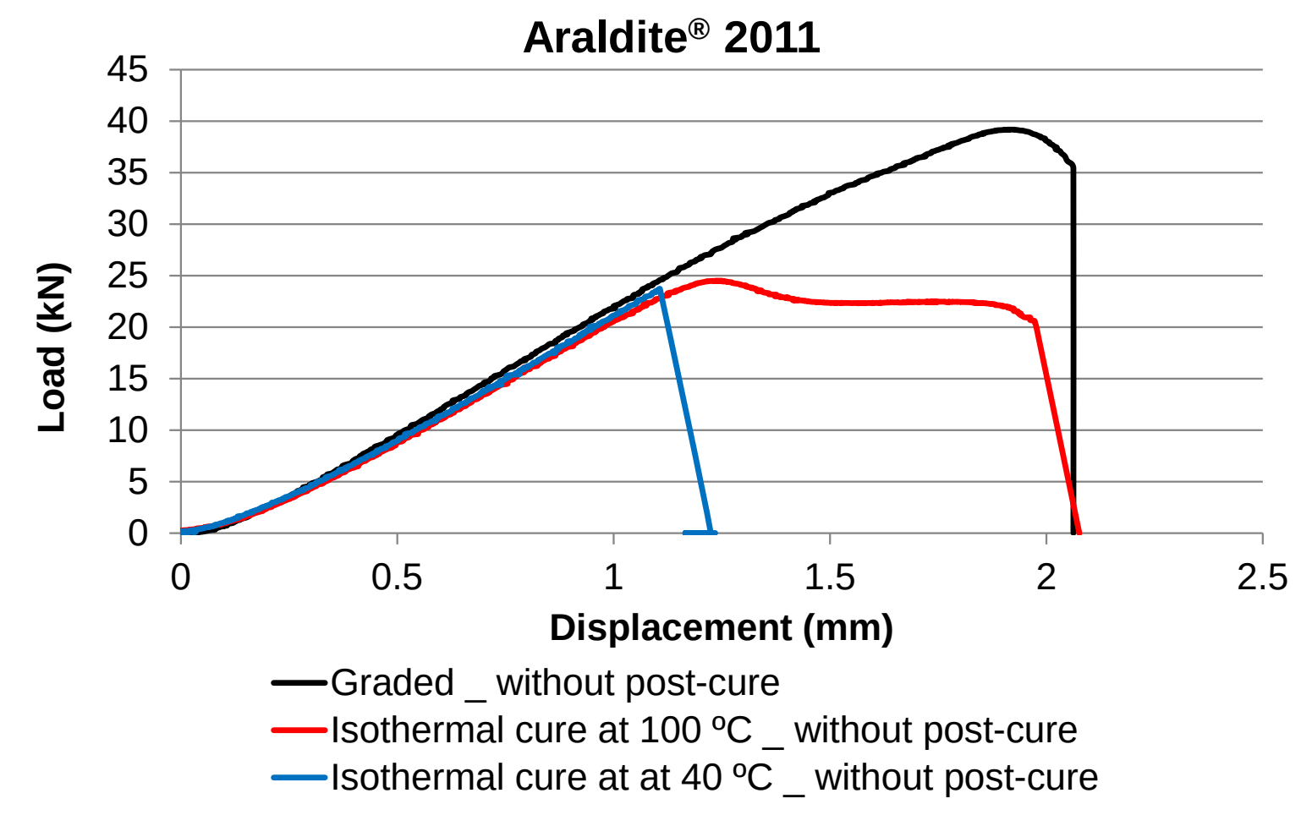
Three different post-curing procedures were considered:

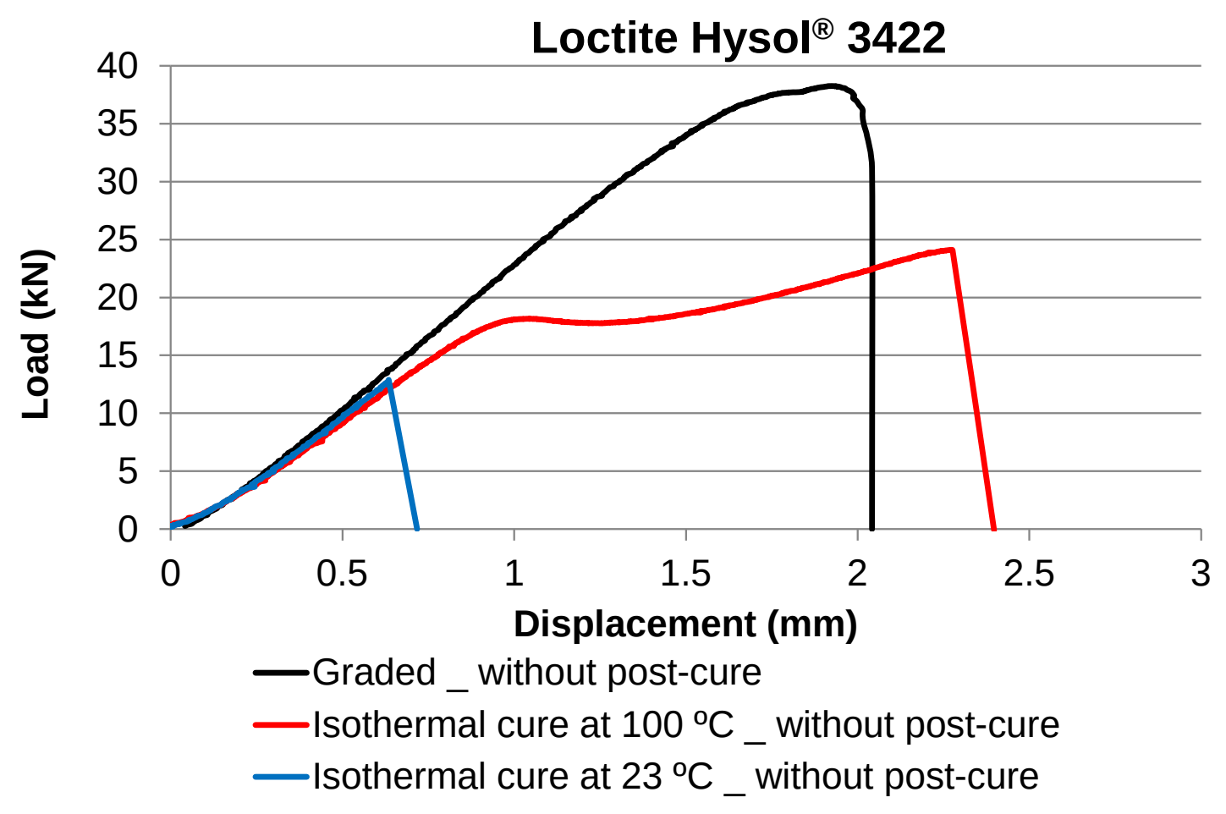
- **First set, the joints were only subjected to a curing process;**
- **Second set, the joints were subjected to a curing process followed by a post-cure performed at a temperature below $T_{g\infty}$;**
- **The third set, the joints were subjected to a curing process followed by a post-cure performed at a temperature above $T_{g\infty}$.**

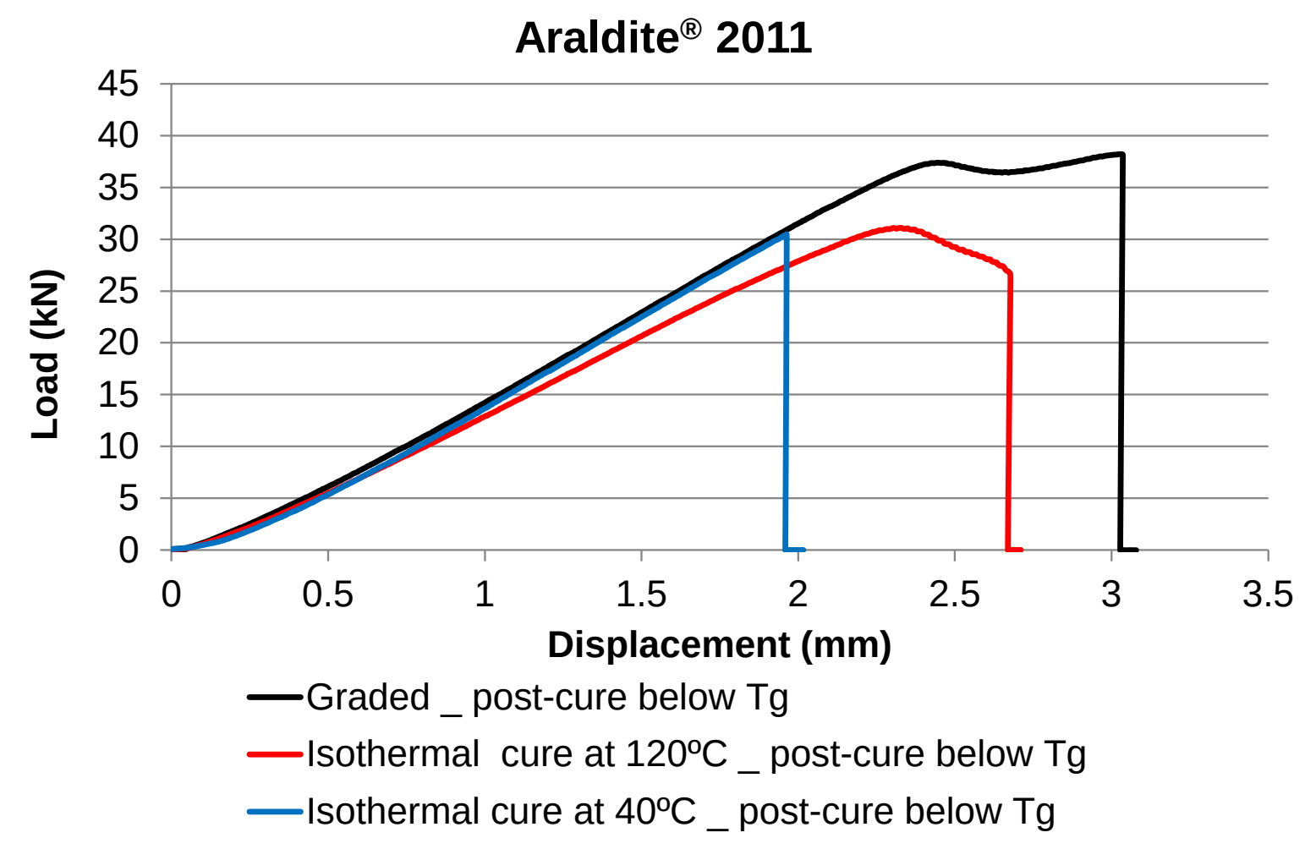
Experimental results

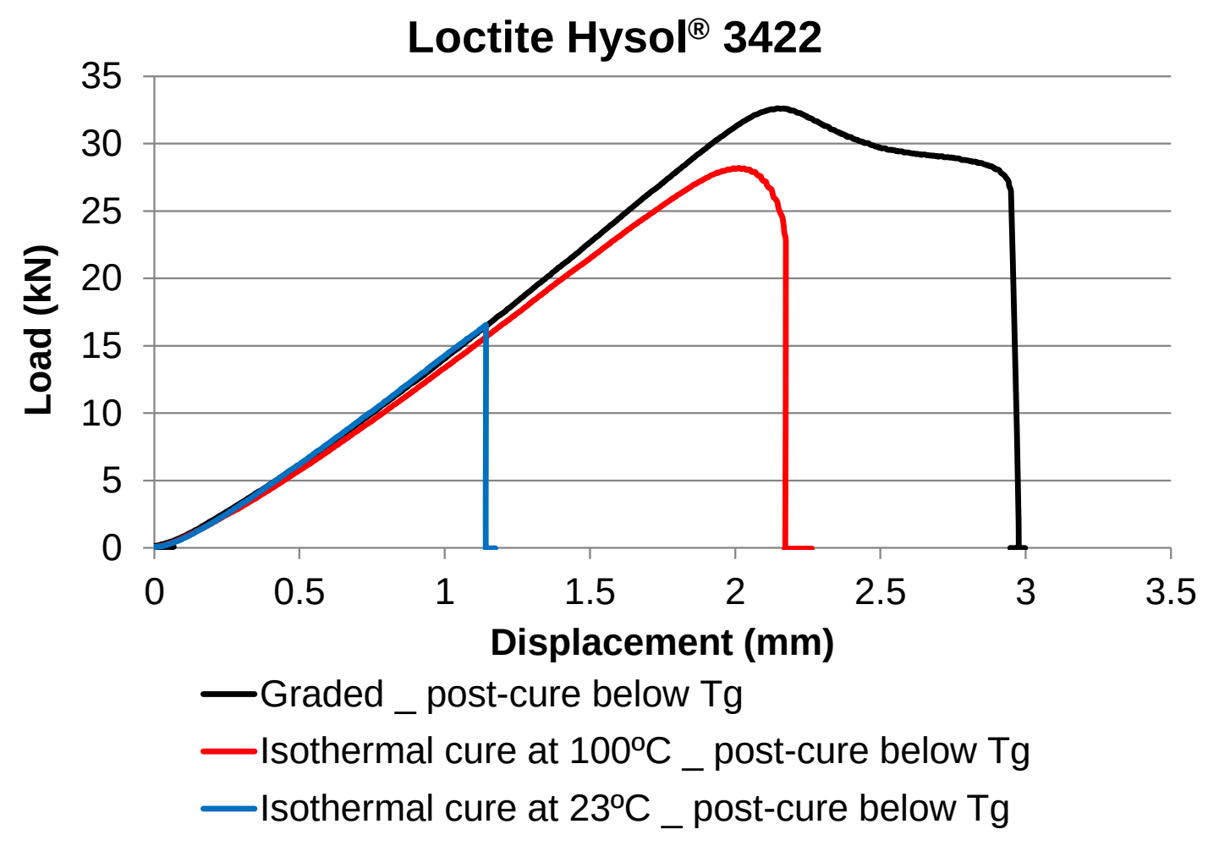
Load-displacement curves

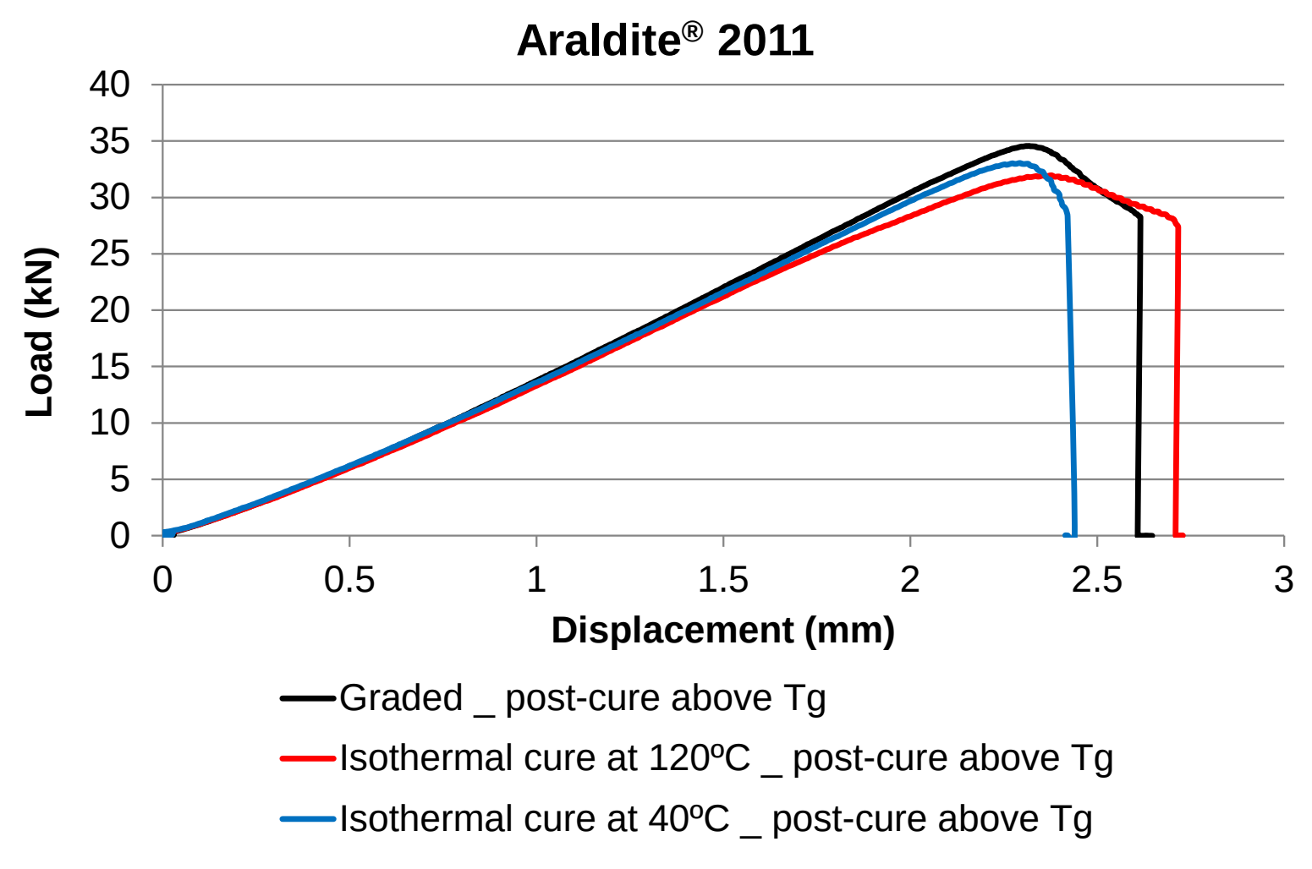
Typical load-displacement curves obtained by tensile tests of the SLJ specimens :

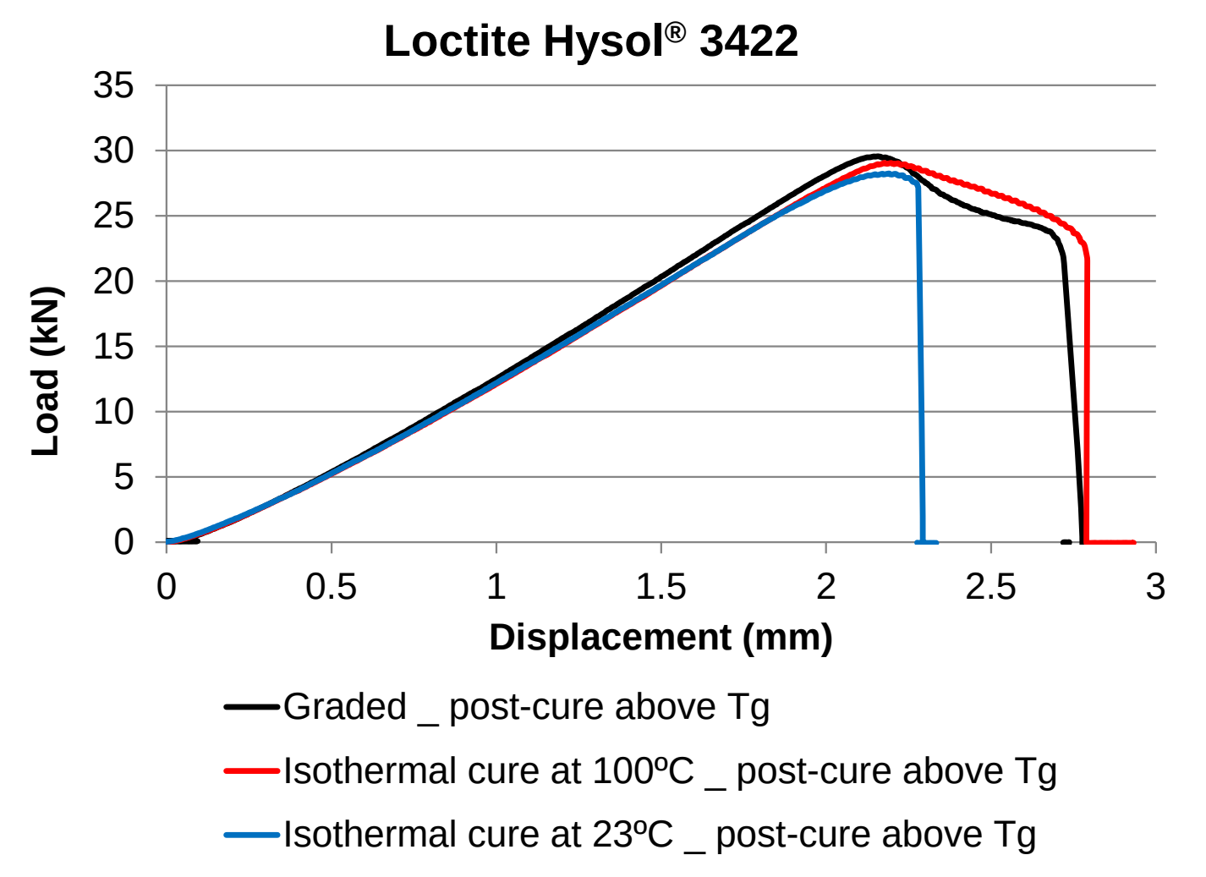




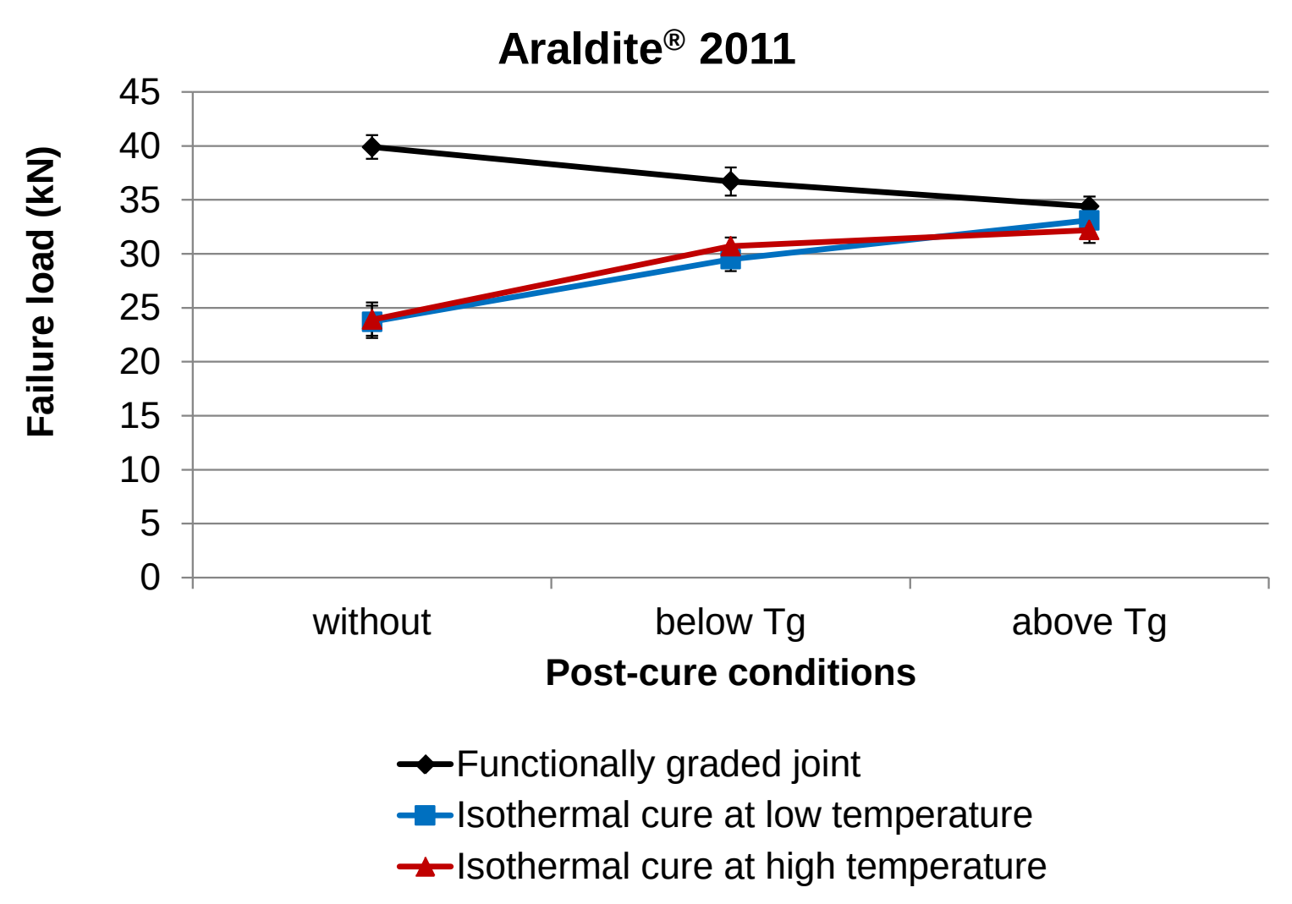


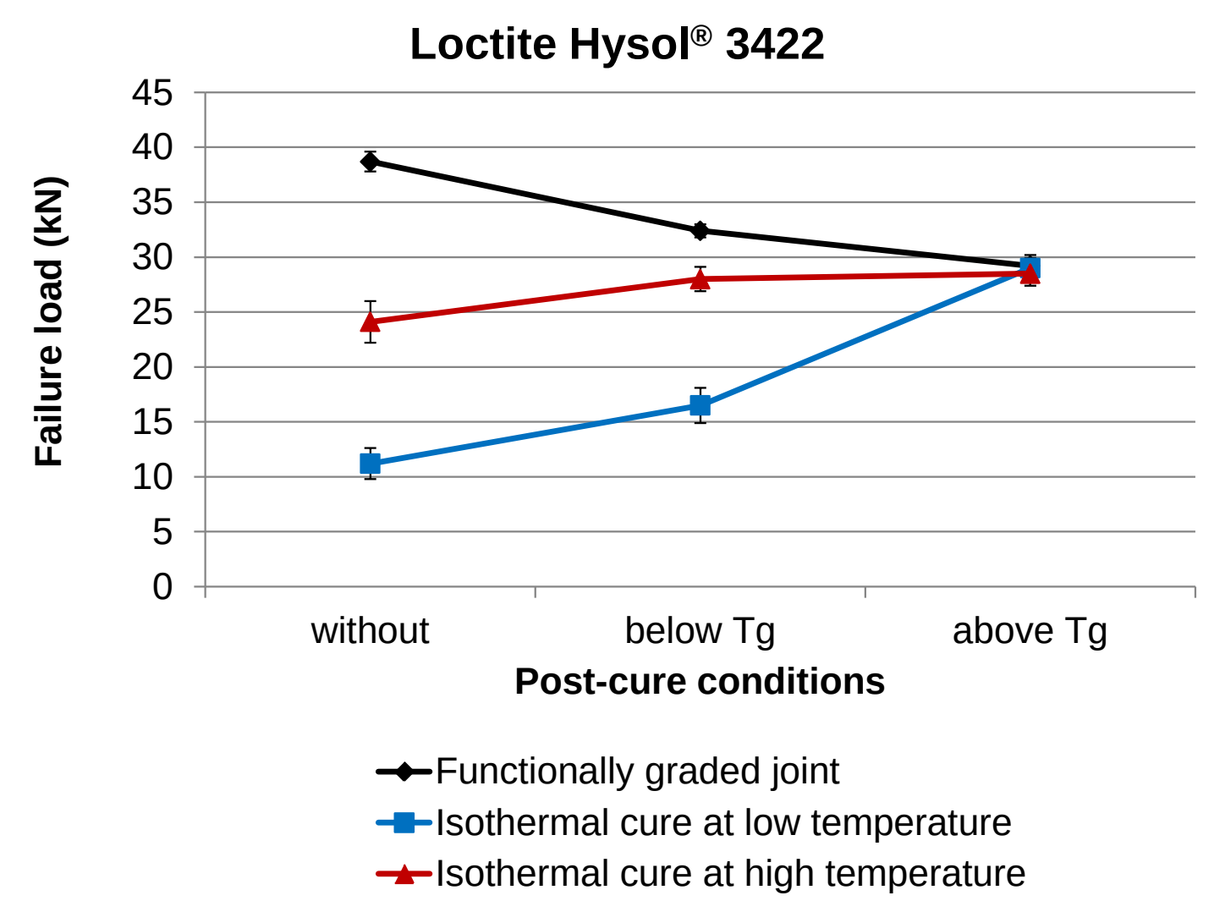






The experimental values of the failure loads when submitted to different post-cure conditions:





Failure load prediction

Isothermal cure

Joints cured isothermally with a ductile type behaviour → global yielding criterion [5]

Joints cured isothermally with a brittle type behaviour → Volkersen's model [6]

Graded cure

Joints cured gradually → simple analytical analysis proposed by Carbas *et al*. [7]

		Araldite® 2011			Loctite Hysol® 3422		
		Experimental (kN)	Predicted (kN)	Error (%)	Experimental (kN)	Predicted (kN)	Error (%)
Without post-cure	Functionally graded joints	39.9	37.5	5.5	38.7	36.5	5.7
	Isothermal cure at low temperature	23.7	18.5	21.9	11.2	16.2	44.6
	Isothermal cure at high temperature	23.9	21.9	8.4	24.1	22.0	8.7
With post-cure – below $T_{g\infty}$	Functionally graded joints	36.7	34.6	5.7	32.4	31.1	4.0
	Isothermal cure at low temperature	29.5	28.9	2.0	16.5	16.3	1.2
	Isothermal cure at high temperature	30.7	28.2	8.1	28.0	26.3	6.1
With post-cure – above $T_{g\infty}$	Functionally graded joints	34.4	32.5	5.5	29.2	28.0	4.1
	Isothermal cure at low temperature	33.1	31.3	5.4	29.0	27.5	5.2
	Isothermal cure at high temperature	32.2	29.9	7.1	28.5	26.9	5.6

Conclusions

In this study, joints with the adhesive gradually modified along the overlap submitted at different post-cure conditions were studied and compared with joints cured isothermally at different temperatures. The following conclusions can be drawn:

1. **The analytical model proposed by Carbas *et al*. [7] shown to be a useful tool to predict the failure load of the functionally graded joints (submitted or not at any post-cure conditions);**
2. **For the same post-cure conditions, the functionally graded joints show the highest failure load and similar displacement than the joints with ductile adhesive behaviour;**
3. **The functionally graded joints bonded with Araldite® 2011 and Loctite Hysol® 3422 showed a high performance gain when not submitted to any post-cure conditions in comparison to the joints cured isothermally at low or high temperatures;**
4. **For post-cure below $T_{g\infty}$, the joints cured gradually show a slight decrease of the failure load and those cured isothermally show an increase of the failure load value;**
5. **With an increase of the temperature of post-cure (above $T_{g\infty}$), the joints cured gradually and isothermally tend to show similar failure load values;**
6. **Therefore it can be concluded that the functionally modified adhesive properties are lost when the joint is subjected to a post-cure above the $T_{g\infty}$. To ensure that a functionally graded joint is obtained, the temperature of post-cure that it is subjected must be below $T_{g\infty}$.**

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