# OVERVIEW OF MODE I STRAIN ENERGY RELEASE RATE CALCULATION FOR ADHESIVE JOINTS

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**Keywords:** Adhesive, Strain energy release rate, Double cantilever beam.

**Abstract.** *To obtain the Strain Energy Release Rate (SERR) of an adhesive in a joint is not a trivial task. Several factors like adhesive thickness, adhesive type (ductile or brittle), and different compliance methods are involved that can affect the final results, most of these factors are implied and not given the proper attention on the standards, which can misguide new researches leading to dubious results. The purpose of this work is to present these factors and their respective impact when calculating the SEER. Results show that the strain energy release rate may not represent a general adhesive property but a particular property for the specific joint in the analysis.*

## 1. INTRODUCTION

Technology evolution in most engineering fields requires the combination of lightweight structures with great mechanical resistance, especially in aeronautical structures, which weight reduction reduces fuel consumption and increases payload capacity. Structural weight reduction can be achieved by the use of advanced materials and fabrication methods, such as 3D printing, composite materials, and the use of adhesively bonded joints in place of classical mechanical fastening methods. By contrast, the bonding technique allows for the possibility of union complex geometries, uniform stress distribution, and better structural performance, however, wider use of this technique is still restricted by the lack of reliable failure models, inducing oversized and reinforced joint designs due to safety factors [1]. The existence of reliable techniques to predict the strength of an adhesive joint is essential to validate a structural project. In addition to knowing the stress distribution in the adhesive layer, from a fracture mechanics point of view, it is also essential to know the Strain Energy Release Rate (SERR) or fracture energy of the adhesive material, which represents the energy necessary for the propagation of an existing crack. When calculating the SERR using conventional standards [9,10,11], experimental results may differ from those predicted by classical analytical models, suggesting the existence of some parameters that may influence the SERR calculations that there are not specified in those standards. The purpose of this work is to present some of these factors and their respective impact when calculating the SERR.

## 2. THEORETICAL OVERVIEW

For a known crack size, to predict the onset crack propagation of an adhesive joint the SERR must be calculated. It has direct relation with the fracture separation modes, Mode I and Mode II components, representing respectively the crack opening due to normal forces and crack propagation due to sliding shear [2]. In most standards eg. [9-11], to calculate the fracture energy of a specified separation mode, the usual procedure is to obtain relations between specimen width, compliance, load and crack length of a pre-cracked specimen. These models used to calculate the fracture energy of bonded joints are based on classical beam-theories and linear elastic fracture mechanics. Analytical and experimental results have a good agreement when working with bulk materials, in practice, however, an adhesive is a thin layer, part of a system to join different substrates together to resist separation [12], thus, experimental results may differ from those predicted by classical analytical models. It is not hard to find different results about the same adhesive, even using similar test parameters. Take for example works that investigated the SERR in Mode II of a common two-component epoxy paste adhesive Araldite 2015 (Huntsman®) [4-8], all using the End Notched Flexure method (ENF), similar adhesive thickness ($t_a$) and in some cases different adherent materials. The results presented in Tab. 1 show that there is no trend in define precisely which one is the "right" value for the SERR in Mode II of the Araldite 2015 adhesive. Results also show that there is a dependence of the adhesive thickness on the SERR and there is a trend in composite adherents to exhibit lower fracture energies than metal adherents. Da Silva et al. (2011) [12] alerts the use of the SERR of other researchers data for modeling purposes, the properties used in simulations should be determined in conditions similar to those to be modeled, this aspect is often not taken into account and may lead to erroneous results.

Table 1 – Differences found on the SERR in Mode II for the commercial epoxy adhesive Araldite 2015 (Hunstman®)

| Method | Adherent | Adhesive | $t_a$ $[mm]$ | $G_{IIc}$ $[N/mm]$ | Work |
|---|---|---|---|---|---|
| ENF | ALUMINUM | Araldite 2015 | 0.2 | 2.97 | Azevedo [4] |
| ENF | CFRP* | Araldite 2015 | 0.2 | 4.70 | De Moura et al.[5] |
| ENF | CFRP | Araldite 2015 | 0.2 | 4.60 | Moreira et al.[6] |
| ENF | CFRP | Araldite 2015 | 0.2 | 5.06 | Figueiredo et al.[7] |
| ENF | STELL | Araldite 2015 | 0.2 | 7.15 | Da Silva et al. [8] |
| ENF | CFRP | Araldite 2015 | 0.5 | 7.71 | Figueiredo et al.[7] |
| ENF | CFRP | Araldite 2015 | 0.5 | 11.90 | Da Silva et al. [8] |
| ENF | CFRP | Araldite 2015 | 1.0 | 10.05 | Figueiredo et al.[7] |
| ENF | STELL | Araldite 2015 | 1.0 | 32.40 | Da Silva et al. [8] |

*Unidirectional carbon-fiber-reinforced plastic.

These results presented in Tab. 1 also suggest that are some hidden or negligible factors that must be considered when performing fracture energy tests, therefore, further investigation must be made. In adhesive joints, Mode I receive more attention since it provides small energy fractures compared to Mode II, so only Mode I SERR will be considered in the present work. Factors like temperature, cyclic loading, and environmental conditions also play an important role in the fracture's energy, but since they are considered special cases, they will not be covered in this work.

Consequently, when working with adhesive joints, one must be paying attention to influences other than those described on the standards, as shown in Fig. 1.

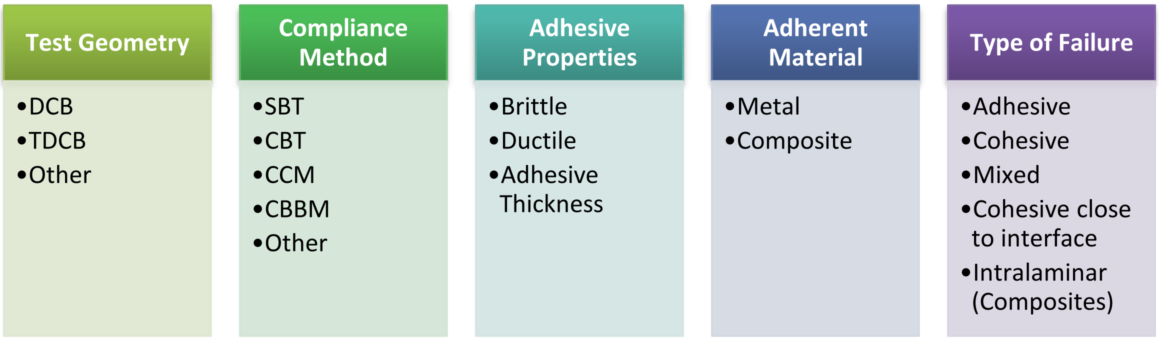


Figure 1 – Principal factors that can affect SERR results for a Mode I adhesive joint.

The most common and acceptable test geometries used for characterization of fracture energy in Mode I are the Double Cantilever Beam (DCB) and Tapered Double Cantilever Beam (TDCB) [13], but they are not unique, in fact, any test geometry can be used, provided that its compliance is known. There are several approaches to obtain specimen compliance, in summary, SERR models are based on the Irwin-Kies equation using experimental compliances methods or by using simple or corrected beam theory [12]. The beam theory approach requires corrections to be implemented to take into account some effects that occur on the bonded joint that are not considered in the original model, like shear effects and crack root rotation [12]. These corrections make the way for several compliance calculation methods, each one takes into account some effects not considered in the previous models, the most common compliance methods are shown in Tab. 2, more can be found in the work of Chaves et al. (2013) [13].

Table 2 – Description of the most common compliance methods

| **Compliance method** | **Effect Correction** |
|---|---|
| Simple Beam Theory (SBT) | Correction for shear effects |
| Corrected Beam Theory (CBT) | Correction for shear effects and crack root rotation |
| Experimental Compliance Method (ECM) | Correction for shear effects and crack root rotation |
| Compliance Based Beam Method (CBBM) | Crack equivalent method with correction for shear effects and crack root rotation |

Blackman et al. (2003) [14] performed an inter-laboratory round-robin test program to check differences in the SERR obtained by different Compliances methods (SBT, CCM, CBT), test geometry (DCB and TDCB), and test material (mild steel, aluminum, and CFRP). Samples were dived between 10 laboratories to reduce personal operator sensitive influence on the results. The results showed that system compliance effects (in addition to specimen compliance) can have a great influence on the analysis and must also be corrected. Corrected Beam Theory (CBT), implemented on the ASTM D3433 [9], was shown to be in error, leading to very conservative values. Values of SERR show to be independent of the test geometry and specimen material, however, Blackman et al. (2003) [14] alerts that the existence of pre-bond moisture in CFRP adherents can change the glass temperature transition ($T_g$) of the adhesive, strongly decreasing the SERR [15,16].

### 2.1. Adhesive type and thickness influence

There is no single trend to describe the dependence of the fracture energy of adhesive joints on bonding layer thickness [18]. In summary, ductile adhesives have greater fracture energies than brittle adhesives due to the plastic deformation zone occurring at the crack tip, showing more stable crack propagation. Bascom et al (1975) [17] investigated the effect of bond thickness on Mode I fracture behavior of an adhesive joint, concluding that the fracture energy increases which the increase of adhesive thickness, reaching its peak when bond line thickness was about the size of the plastic zone formed at the crack tip. Kinloch (1987) [19] concludes that an increase in adhesive layer thickness has no significant influence on the fracture energy of brittles adhesives, however, fracture energy of ductile adhesives seems to increase whit increase of bond line thickness, the same trend was found in [8,18]. This effect is more perceptive on small thickness, the fracture energy can reach a plateau or decrease after a certain thickness.

Fernandes (2019) [18] concludes that fracture energy is strongly dependent on the crack path and surface morphology. It is common to the crack front to show a tendency to propagate with an alternating trajectory, changing and combining types of failure (cohesive, adhesive, or both) and therefore the SERR.

## 3. CONCLUSION

To obtain the fracture energy of an adhesive in a joint is not a trivial task. Several factors like adhesive thickness, adhesive type (ductile or brittle), and compliance methods are involved that can affect the final results, most of these factors are implied and not given the proper attention on the standards, which can misguide new researches leading to dubious results. The strain energy release rate of adhesive joints can be affected by system compliance (or machine compliance), type of adhesive (ductile or brittle), the thickness of the adhesive layer and crack failure path. Simple beam theory must be avoided and a more accurate method should be used instead (CBT or ECM). Laminated composites substrates must be used with caution since pre-bond moisture in composites can change the glass temperature transition of the adhesive. If a message is intended, it is to convey that adhesive SERR is very sensitive to the joint parameters and may not represent a general adhesive property but a particular property for the specific joint in the analysis.

## ACKNOWLEDGEMENTS

The authors are thankful for the support of the Coordination for the Improvement of Higher Education Personnel (CAPES).

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