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# Advanced Joining Processes Unit: A Fully Independent Research Group

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**Abstract**

The Advanced Joining Processes (AJP) is an autonomous research unit at the Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI) that works closely with the Faculty of Mechanical Engineering of the University of Porto (FEUP). This unit is staffed by professors, post-doctoral researchers, PhD students, MSc students and research fellows. The AJP unit has four key competences, established to support all aspects related to the study of advanced joining processes: testing, simulation, production and machine design. The AJP unit has robust and fully independent competences in the manufacture of experimental specimens and components. The unit operates a fully equipped laboratory with all facilities necessary to manufacture specimens, moulds, test fixtures and testing equipment. The unit has extensive experience in testing complex specimens' geometry under a wide range of conditions. Research is carried out to determine the performance of structural joints under quasi-static loads, high strain rates, fatigue and creep conditions, among many others. Complementarily, the unit also has a strong machine design capability, being experienced in the development and manufacture of custom designed testing equipment (such as creep testing machines, drop-weight testing machines, torsion testing machines, split Hopkinson pressure bars and devices for glass transition temperature measurement). These experimental capabilities are complemented with robust numerical simulation competencies, which allow to streamline the design process by creating powerful models that can accurately predict the mechanical behaviour of advanced structural joints. These capabilities enable the AJP unit to undertake new and challenging research projects, reacting quickly to current industrial demands and scientific trends, due to its autonomy. This work methodology allows the AJP unit to simultaneously operate in two main fronts. One is fundamental academic research, resulting in MSc and PhD thesis and scientific publication, and the other is comprised of knowledge-transfer activities with industrial partners, which generate funding that can be used to support additional fundamental research. By combining these two approaches, the AJP unit proves that sound technological based educational processes can be achieved while undertaking cutting edge research with practical and industrial value.

**Author Keywords**. Research Group, Production, Testing, Simulation, Machine Design.

**Type**: Research Article


## 1. Introduction

In the late 19th century universities began to include significant scientific research in its activities, where it acted as a complement to its education activities. Later on, by the early

20th century, universities assumed a more significant role in research, to the point where this activity was now key for funding the higher learning system. An entrepreneurial academic format was eventually established, generating knowledge and technologies that were transferred to the industrial sector, stimulating societal advance and overall productivity. The research group initially consisted in a formal or informal collaboration between several researchers with the purpose of working on a set of projects related to a research problem. Miller (1979) considered that the knowledge and research skills are 'most effectively transmitted through the collective efforts of interdependent groups of scholars'. Also, Etzkowitz (1992) described research groups as 'the engine of productivity in research and of effective graduate training in universities'. Currently, research groups have become more commonly characterised by personal autonomy and networked collaboration with other research groups and industries. Research groups allow for increased collaboration between researchers, increase the quality of research, create permanent jobs in academic positions, and promote the development of externally financed research projects (e.g. government or industrial sources). Research groups are essential to raise the reach and impact of research, which will also benefit the educational activities developed in research universities (Etzkowitz 2003). However, it must be noted that some authors, such as Fox and Faver (1984) suggest that cooperation activity cannot be seen as purely advantageous, as it hinders freedom and creativity in the research project and can indeed have negative effects.

Crede and Borrego (2012) evaluated how research groups foster successful learning and professional development for graduate engineering students. They concluded that the group size influences the mechanisms of student learning and practices are recommended to create an environment that fosters successful learning and professional development. Large groups provide the student with access to resources such as personnel, equipment, and materials, which will exponentially accelerate the learning curve of the students. These large research groups provide numerous benefits to graduate students, such as a first experience of independent academic work, the possibility to cooperate with industrial partners at a high scientific level; the opportunity to publish the developed research work and, lastly, the opportunity to attain goals that can be difficult or impossible to achieve when working in isolation or within smaller research groups (Turner 2006).

The Nordic Institute for Studies in Innovation, Research and Education performed a survey among the permanent academic staff in universities in 2013 at different research groups in different areas such as humanities, social sciences, natural sciences, technology and medicine and health. They concluded that established research groups allow to develop high quality studies and play an important role in doctoral and master dissertations (Vabø et al. 2016). Research groups allow the scholar community to develop intellectually stimulating activities.

In sum, one of the hallmarks of a successful research group is its capability to fully leverage its human and material resources to operate efficiently and quickly respond to new research trends and meet industrial requests. The research group under discussion in this paper is the Advanced Joining Processes (AJP) unit of the INEGI/FEUP, a multidisciplinary research team, composed of post-docs, PhD students and MSc students. The AJP unit has extensive experience in solving problems associated with adhesive joining and in supporting industrial entities who wish to implement this technique in their products. The work carried out by this unit is extensive and covers mechanical characterization of adhesives, especially in terms of fracture toughness, adhesive joint modelling with analytical models and finite element analysis supported by careful experimental testing. This unit is also capable to develop novel testing equipment, especially well-suited to test adhesive joints. All these competences were developed to ensure that the group can act independently in research activities and can use these abilities to accelerate processes and perform quick decision making. Note that this does not mean that the group operates fully alone or that it never works in cooperation. In fact, what it means is that the group has identified a key set of competences which are crucial to its operation, success and that maximize its impact, and has chosen to strengthen and grow around these competences. This manuscript describes how a research group, more specifically the AJP unit, can ensure its independence and how it can explore this characteristic to become agile in its processes. A case study is also included, to highlight the advantages of this process.

## 2. Definition of Core Competences

When a research group initiates a new research project, it almost always starts by defining the basic research problems and identifying the different hypothesis that will drive further research. As consequence, a suitable work plan can then be formulated and initiated, which will later produce results and eventually lead to main conclusions of the project. To conduct research in the engineering and general technological fields the capability to carry out experimental and numerical procedures is essential. Depending on the extent of their capabilities in this field, research groups can be classified as fully or partially independent. Figure 1 schematizes the main differences that exist between a fully or a partially independent research group.

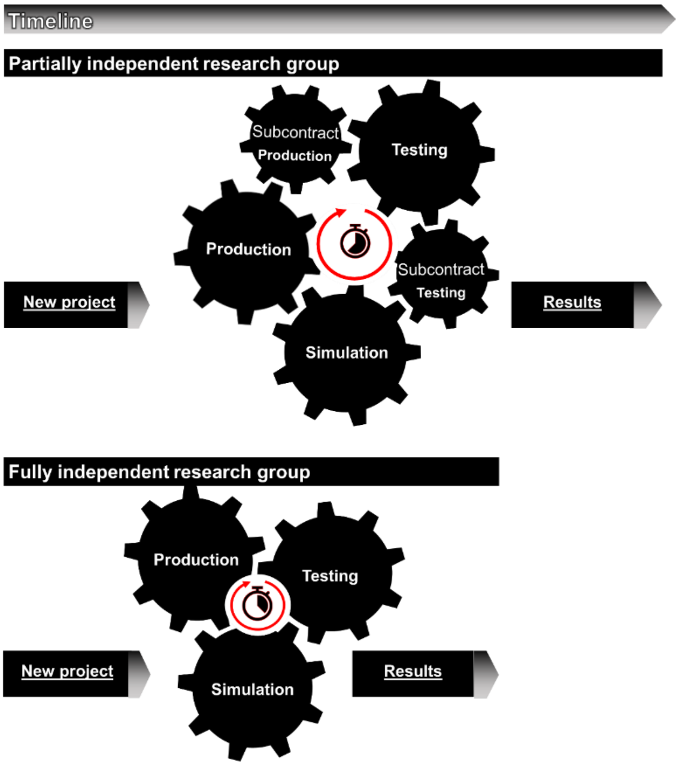



**Figure 1**: Differences of fully and partially independent research group

Fully independent groups are characterized by complete independence in a core set of main competencies. In an engineering field, these are typically competences in specimen production an manufacture, testing procedures, which is achieved with adequately trained personnel and laboratories equipped with all the necessary equipment and lastly, equipment design capabilities, which enable the development of new testing devices or carry out modifications on existing equipment. In parallel, competences in simulation procedures and numerical modelling are also often essential, as these allow to quickly analyse complex problems and perform optimization procedures, without the need for costly additional experimental testing.

In contrast, partially independent groups often do not master all or at least some of these competences and require the establishment of partnerships or subcontracting experimental and/or numerical work to be able to successfully attain specific research goals. It is important to note that these outsourced activities will act as significant interruptions in the project' workflow, which represents time delays, added costs and a greatly diminished response capability of the group.

The AJP unit has been set up as a fully independent group, achieved by acquiring competences in four different main fields, highlighted in Figure 2. These competences allow the group to be able to perform cutting edge research in the field of joining and to be able to quickly react to industrial challenges in the adhesion and joining fields.

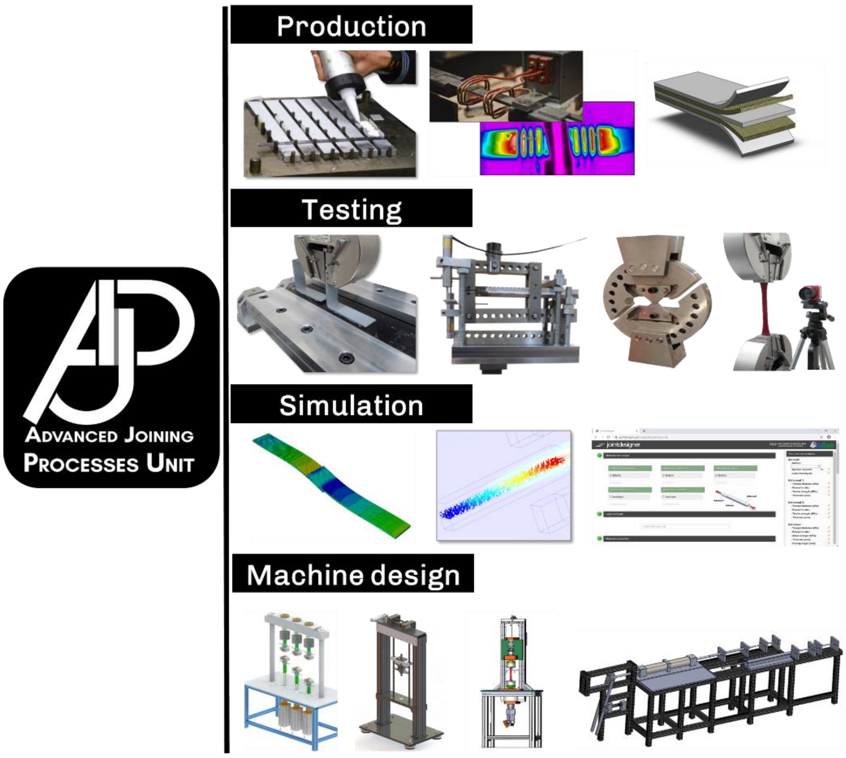
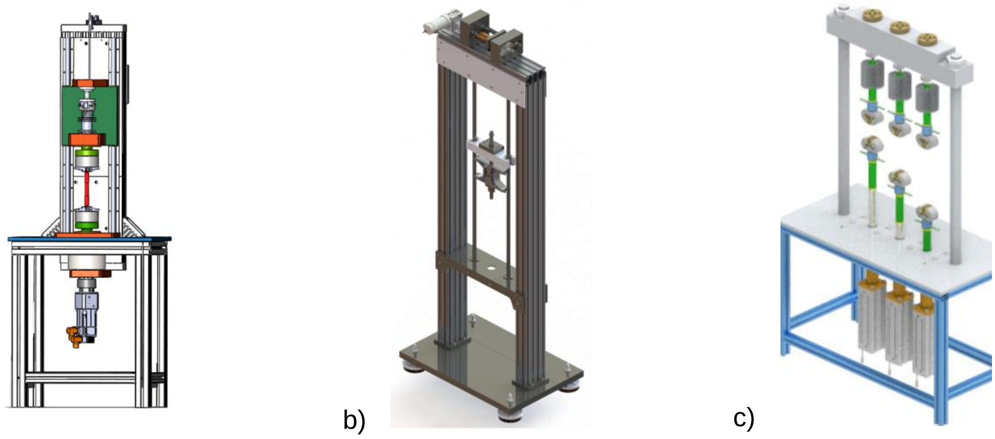



**Figure 2**: Competences of AJP unit

To better illustrate the capabilities the AJP unit, the following sections detail the some of the techniques, equipment and tools developed by the unit members (both permanent researchers and students) which enable the AJP unit to work fully independently. The equipment and the tools necessary to carry research work in a quick and agile manner are highlighted, supporting high quality research work and allowing to effectively answer to requests from industrial partners. This is highly important because although the unit carries out fundamental research sponsored by governmental entities, it is also supported by extensive consulting work with several different industrial partners. Providing a quick yet scientifically sound response to the challenges raised by industrial partners is only possible with a stable and multidisciplinary human resource structure, built upon fundamental knowledge, supported by extensive experimental equipment and with the capability to operate 24 hours per day if necessary.

### *2.1. Machine design*

The AJP unit has developed competences in machine design, benefitting from a structure that includes professors and post-doctoral researchers which are experts in the different fields of mechanical engineering, such as automation, structural design, and material science. By mastering these fields it is possible to explore synergies that allow to develop novel equipment. This includes advanced testing machines to characterize adhesives and adhesive joints (such as torsion testing machines showed in Figure 3a (Dantas et al. 2021), drop-weight testing machines showed in Figure 3b (Antunes et al. 2019), creep testing machines showed in Figure 3c (Janeira et al. 2020), Split Hopkinson pressure bars and devices for glass transition temperature measurement). The development of such equipment is always carried out in the context of student thesis and projects, which play a key role in integrally developing the components, always under the supervision of the AJP unit members. This allows the students to experience first-hand the processes and methods which must be mastered in the design of advanced testing machines, as well as the challenges associated with these activities. As stated before, this equipment later plays a critical role in supporting innovative research work on adhesively bonded connections and allows the unit to be independent and agile on its operation.



a) b) c)

**Figure 3**: Schematic representation of: a) torsion machine (Dantas et al. 2021), b) drop weight impact testing machine (Antunes et al. 2019), c) multi-station creep testing machine (Janeira et al. 2020)

### *2.2. Production*

Another key group competence is in the manufacture of specimens. In order to be successful in material characterization processes, the research group must be able to independently manufacture high quality specimens, from smaller, standardized specimens to more complex constructions, highly representative of actual components. This requires significant investment in equipment, such as CNC milling machines precision scales, centrifugal mixers and surface treatment equipment. Surface energy measurement equipment is present to immediately assess the effectiveness of the performed treatment. Several custom designed moulds are available to precisely control the geometry of the joints during the cure process. Finally, curing equipment, such as hot-press, environmental chambers and induction coils are also available, some of which are also in-house developed. Such equipment and capabilities are combined with carefully designed procedures and lead to highly reproducible tests, which are essential to ensure the validity of all research work being conducted.

This type of work also opens the door to innovation in processes and has led to several provisional patents' requests. These include methodologies to obtain functionally graded joints using differentiated cure (Figure 4a) or gradually reinforced with magnetic particles

(Figure 4b) and to develop new, high toughness, composite laminates (Figure 5). The development of these techniques was the main topic of several PhD thesis, where particular aspects of bonded joints were finely controlled, tuned and optimized in view of attaining increased joint performance in comparison with industrially standard techniques (Carbas, da Silva, and Critchlow 2013; Barbosa et al. 2019; da Silva et al. 2018).

a) b)

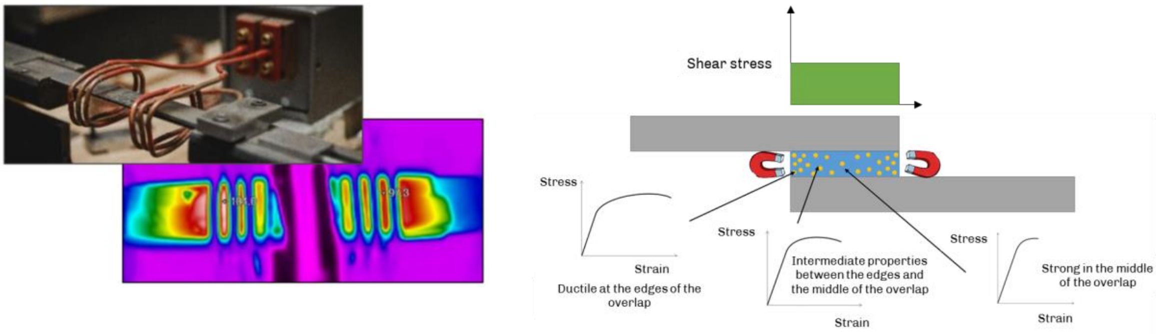



**Figure 4**: Functionally graded concepts, a) special induction coil to obtain a graded cure (Carbas, da Silva, and Critchlow 2013) and b) graded magnetic field to disperse gradually magnetic particles (Barbosa et al. 2019)

a) b)

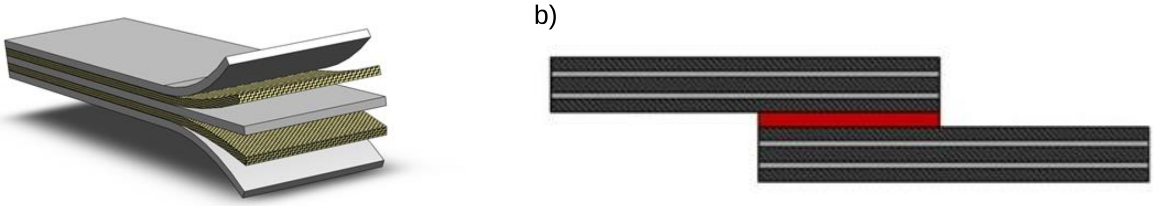


**Figure 5**: Composite stacking illustration a) and hybrid joint with toughened composites b) (da Silva et al. 2018)

### *2.3. Testing*

Material and joint testing is other major competence where the AJP unit has developed substantial expertise. Many different commercial setups are available for material testing, designed and supplied by the specialized manufacturers. However, most of this equipment is not suitable for use with adhesive joints, requiring major changes to better handle the specificities of these joints. In light of these limitations, the AJP unit is constantly improving its testing capabilities by undertaking development work of novel testing devices and jigs, all optimized to test adhesive joints and able to extract highly useful material data under a wide range of conditions. Mechanical and video extensometers are available to measure the local deformation of specimens, linear and even laser transducers to record the displacement of a specific point of interest at very high speeds (for example, during an impact test). Overall, a large range of tests setups is available, enabling the determination of the strength and fracture of materials and joints. To develop this equipment, the unit relies on the know-how of its permanent members and the contributions of its students, which also help to design some of these innovative solutions. This wide range of highly novel tests enable the unit to carry out many different types of test.

Two specific examples of testing apparatus developed by AJP unit are mixed mode fracture energy testing apparatus and a device for testing dismantlable adhesives. These are detailed in the following paragraphs.

The novel mixed mode testing apparatus, suitable to determine the fracture energy envelope of adhesives, was developed in the context of a PhD thesis where the candidate was able to numerically validate the testing procedure and compare its performance against other conventional methods available in the literature (Costa et al. 2017). Due to its simplicity (Figure 6), this method has attracted the attention of both academics and industrial users. Currently, a set of research centres and vehicle manufacturers already use this method to characterize the fracture envelope of structural adhesives.

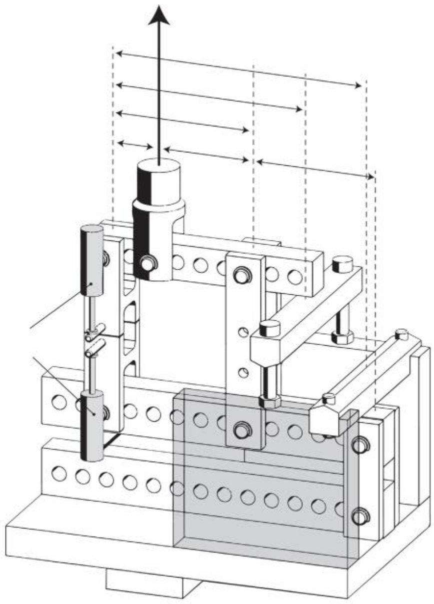


**Figure 6**: Schematic representation of the mixed mode apparatus (Costa et al. 2017)

The development of joint dismantling techniques represents a path to ensure the recyclability of bonded structures. This technique was first developed by MSc candidates, integrated in a larger research work, where the main purpose of the project was the development of a technological solution suitable to dismount a well-defined area bonded area (Figure 7). This should be attained using the lowest temperature possible, while ensuring that any modifications made to the joint or the adhesive do not have a significant performance penalty (Banea, da Silva, and Carbas 2015).

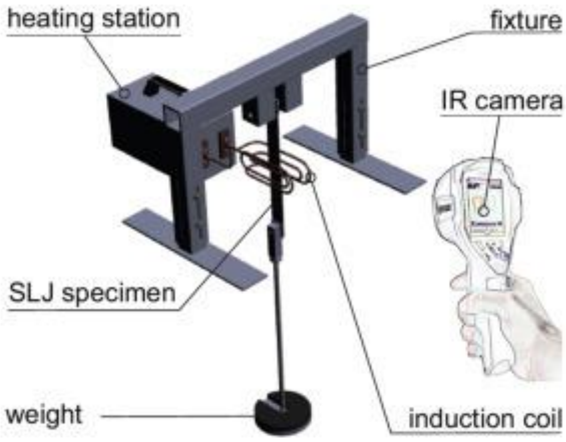



**Figure 7**: Dismantling apparatus (Banea, da Silva, and Carbas 2015)

### *2.4. Simulation*

Although all of the previously described competences are mostly experimental in nature, research work carried within the AJP unit is not solely restricted to this aspect, as the unit also possesses strong numerical simulation capabilities. The work of the AJP unit on simulation of adhesively bonded joints is extensive and includes different approaches to predict bonded joint behaviour. Such methodologies can be used to streamline the design process and create effective models that can accurately predict the mechanical behaviour of advanced structural joints. The unit employs powerful finite element software commercial software such as Abaqus, Matlab or Python codes, but it has also developed custom finite element codes and standalone software to predict the mechanical behaviour of adhesive joints, using suitable analytical models. The modelling activities followed by the AJP unit can by divided into analytical and numerical methodologies. Although limited in their scope, analytical methods are quite powerful for some specific joint design cases and the AJP unit has significant expertise in the application of analytical models, including the development of software that simplifies its use. Regarding numerical modelling, the AJP unit uses a combination of finite element analysis commercial software and custom designed finite elements that offer improved capabilities over those implemented in commercial software (da Silva, Öchsner, and Adams 2018; da Silva et al. 2012).

Furthermore, a web interface using analytical models was developed by MSc candidates, drawing upon the combination of knowledge on materials and adhesive joints and on programming that exists in the AJP unit (da Silva, Lima, and Teixeira 2009). Also, a robust numerical tool was developed during a PhD thesis carried out in close cooperation with industrial partners, where it was proven to be a valid tool for use in design of bonded joints (Costa et al. 2019). All component of this software were developed entirely within the group, which highlights how the effort to ensure independent multidisciplinary capabilities can lead to innovative solutions.

The AJP unit is thus a research group which is able to operate independently and balance fundamental research work with applied research, based on industrial demands. By mastering these four key competencies it has been possible to provide a full independent response for every type of adhesion problem that arise in industrial settings. However, it is vital to understand that such posture is only possible by ensuring constant evolution and development of the research group, adopting state of the art technologies and being ready to quickly react to changing industrial and academic research trends. It is the aim of the AJP unit to always be equipped with any equipment, technology and tools necessary to work independently and provide a fast and effective response to every project (academic and industrial in nature) where the unit is involved.

## 3. A Case Study

The automotive industry has exponentially increased the use of adhesives for joining structural components, always with the aim of reducing weight, minimizing fuel consumption and reducing $CO_2$ emissions. This can be attained by adopting lighter, multi-material structures which lead to higher performing, yet safer vehicles. However, in the design of bonded structures it is essential to evaluate the influence of several combined working conditions that vehicles can be subjected to, such as high strain rates, temperature, humidity, and fatigue. In fact, the behaviour of bonded connections is not well documented and represents a challenge for vehicle designers. To overcome these limitations the AJP unit carried out a project in close collaboration with an automotive manufacturer (Aston Martin Lagonda®) and an adhesive manufacturer (Nagase ChemteX®). During the project, the acquired knowledge was transferred to the industry partners to aid with the development of new products and concepts.

Figure 8 schematically shows the workflow of this project. The project starts with a mechanical characterization of materials, followed by a set of numerical and experimental laboratory joints. It concludes with numerical and experimental tests of a large-scale structural prototype developed during the project. The tasks of the project are briefly described in the following paragraphs, allowing to better understand how the competences of the AJP unit relate with the objectives of each task.

In Task 1, the materials used (adherends and adhesive) were mechanically characterized (both in strength and fracture properties) as a function of loading rate and temperature. The adhesive was also physically characterized, by determining its glass transition temperature. Testing machines specially developed by the AJP unit were fundamental in the adhesive characterisation process. The testing setup was also in-house developed and allowed to properly characterize the adhesive both in bulk and in joint states (Machado, Marques, and da Silva 2018a; Machado et al. 2017a, 2017b; Machado et al. 2019a; Machado et al. 2019b).

Task 2 aims at the evaluation of the performance of laboratory joints under different strain rates at low and high temperatures, conditions typically encountered in automotive industry application. The use of the in-house developed drop weight equipment was essential, as well as the development of a technological solution to control the temperature of the specimen right before impact, using a combination of induction heating and liquid nitrogen cooling. These techniques were shared and validated with the industrial partners and were crucial to ensure the quick execution of the experimental work within a short period of time (Araújo et al. 2017; Machado et al. 2018a; Machado, Marques, and da Silva 2018b, 2018c; Machado et al. 2019f).

The results previously obtained in Task 2 were then used to validate the numerical model developed in Task 3, calling upon the skills existent in the AJP unit with regards to numerical modelling of the strain rate dependent material behaviour. The models were implemented in commercially available finite element code, suitably modified to reproduce the specific behaviour of adhesives loaded under high strain rates (Machado et al. 2020a; Machado et al. 2020b; Machado et al. 2018b; Machado et al. 2018c). Another important point was the evaluation of the performance of aged and unaged joints under static and dynamic loads, performed in Task 4. The production of joints with a well-defined level of humidity is a very important but experimentally complex process. Again, the AJP unit has drawn from its experience in complex ageing processes to complete this process. The scientific knowledge, methodologies and the equipment necessary to age the specimens was already mastered, which allowed to this naturally length phase of the project to progress at a very accelerated pace and in a short period of time (Machado et al. 2020b; Machado et al. 2019c, 2019d; 2019e).

In the final task (Task 5) the performance of the prototype was numerically and experimentally validated under different strain rates. The manufacture process, highly complex due to the intricate joint geometry, was successfully developed taking into account the control of adhesive thickness, substrate alignment and the cure process. The high strain rate test method was made possible by the special design of the drop weight available in the AJP unit, using a newly developed jig that approximates the conditions encountered in real applications. The prototype was fully monitored with sensors to acquire information for the numerical model, drawing on the electronic design and automation competencies of the AJP unit (Silva et al. 2020).

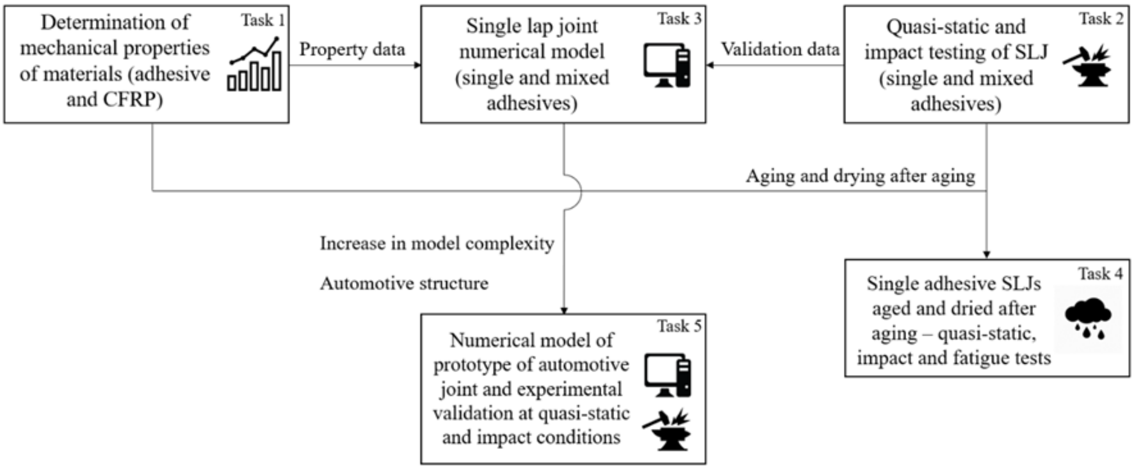



**Figure 8**: Workflow of a research project developed with industrial partners

Although this example is focused on the automotive industry, the AJP unit is able to provide research and development for different industries, using its competences to solve adhesion problems in sectors such as transport, wind, electronic, packaging, shoes industries and adhesive manufacture. These partnerships could only be established upon the knowledge and the competences that were gradually developed and solidified by the unit during its growth and consolidation.

## 4. Conclusions

The main conclusions that can be drawn from the operating mode of the AJP unit, a fully independent research group, are:

- In order to be possible to work in complex research activities and create innovative techniques, equipment and tools it is fundamental to assemble a team that includes personnel with different areas of expertise;
- The in-house development of highly specific devices and technologies allows the unit to respond to complex research demands quickly and efficiently;
- Students can and should be integrated in the work group, where they can expand their competences by helping with the development of advanced equipment;
- An effort must be made so that members of the group are aware of the most recent research trends and constantly update their competences;
- Work developed in cooperation with industrial partners must be carried out in an accelerated pace and this is only possible if the research group masters all the necessary tool and skills necessary for the completion of the project, ensuring that it can work independently and without barriers.

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