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Seismic behaviour of steel structures equipped with traditional and innovative beam-to-column connections

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ABSTRACT

One of the most common ways to conceive seismic-resistant steel structures is by adopting the Moment Resisting Frames (MRFs). This approach ensures that the building withstands the seismic event through the development of plastic hinges at the beam ends, beam-to-column connections or column bases. The most widespread design philosophy relies on the strong-column strong-connection weak-beam approach, which ensures the development of plastic hinges only at the beam ends and first-floor column bases. Nevertheless, this approach implicitly accepts the development of structural damages during a severe seismic event to dissipate the input energy. This is a negative aspect because it affects the reparability and functionality of buildings.

For this reason, in the last decades, as an alternative to this classic design strategy relying on full-strength joints, a new design philosophy based on the use of partial-strength beam-to-column connections was developed. This method relies on the strong-column weak-connection strong-beam approach so that the dissipation of the seismic input energy occurs only in well-defined nodal components, which can be easily substituted at the end of the earthquake. In such a way, structural resilience is also achieved.

Several traditional and innovative solutions have been proposed and investigated within this framework. These beam-to-column joints have been widely studied based on experimental tests, numerical simulations, and theoretical formulations deriving from adequately defined analytical models. In particular, the experimental tests and the corresponding simulations have regarded beam-to-column sub-assemblies under monotonic or cyclic loading histories. In such a way, the basic information related to the analysed joints' stiffness, resistance, ductility and energy dissipation capacity could be easily derived. Instead, very few tests on large-scale steel structures subjected to seismic inputs have been performed.

In this framework, a relevant research programme has been planned at the University of Salerno. It aims at assessing the dynamic behaviour of different beam-to-column connections over the seismic response of large-scale structures. In particular, a significant part of this investigation relates to performing pseudo-dynamic tests on a mock-up building equipped with different traditional and innovative joints: the Reduced Beam Section (RBS or dog-bone) connection; the FREE from DAMage (FREEDAM) joint; the double-split dissipative T-stub (or X-shaped) connection.

The configurations mentioned above represent joints connecting double-tee beam and column profiles, reflecting possible American and European applications. However, since there is widespread use in Japan of tubular columns, configurations connecting hollow sections and double-tee profiles should not remain unexplored. Under this perspective, this thesis also focuses on the static characterisation of joints connecting circular-hollow-section (CHS) columns and through-all double-tee beams by adopting the component method approach. At the moment, the most common way of conceiving such a kind of joint consists of simply welding the beam to the external surface of the column or using collar plates or composite solutions. However, these alternatives do not ensure relevant mechanical properties and simply structural detailing of the connections. Instead, the recent technological advancements introduced the possibility of using 3D Laser-Cutting for manufacturing the joint mentioned above, whose peculiarity is that the beam can intersect the column, enhancing the mechanical properties but with simple nodal detailing. Therefore, the need to study this connection's behaviour through the component method approach relies on the possibility of employing this joint together with other solutions (i.e. RBS, …).

However, because of the incompatibility between the profiles of the columns, the seismic response of this connection cannot be investigated through the same mock-up building used to perform the pseudo-dynamic tests. For this reason, at the end of this thesis, a preliminary and brief introduction to the hybrid simulations with dynamic substructuring technique is reported.

For the sake of clarity, the thesis is divided into six chapters.

Chapter 1 focuses on a brief introduction to the traditional steel frames and beam-to-column joints. In particular, attention is paid to the four connection typologies investigated in the following chapters, and the objectives of the thesis are reported.

Chapter 2 deals with the static characterisation of the Reduced Beam Section (RBS) joint and circular hollow section to through-all double-tee beam connections. In particular, concerning the dog-bone solution, the basic experimental, numerical and analytical activities carried out in the past years at the University of Salerno are reported. Instead, due to the novelty induced by the 3D Laser Cutting Technology, most of Chapter 2 relates to the study of the static behaviour of CHS through I-beam joints. The investigation is based on experimental tests, numerical simulations and analytical formulations concerning the whole beam-to-column sub-assembly and its components. In particular, the components are adequately identified, and formulations to provide their stiffness, strength and cyclic behaviour are reported and implemented through an OpenSees code.

In **Chapter 3**, the basic information related to two innovative partial-strength beam-to-column connections is reported. In particular, the analysed joints consist of the FREE from DAMage (FREEDAM) connection, which is endowed with friction devices, and a joint characterised by dissipative T-stubs which connect the beam flanges to the column flange. The peculiarity of this solution is that the flange of the T-stub is suitably weakened by an hourglass-shaped cut in the zone between the flange-to-stem attachment and the bolts.

In **Chapter 4**, three experimental campaigns concerning pseudo-dynamic tests on a large-scale steel structure equipped with RBS, FREEDAM and X-shaped T-stub connections are discussed. All the experimental data are complemented with numerical simulations developed through SeismoStruct, OpenSees or Abaqus software. In this case, the tested mock-up has been conceived to be demountable so that the connections could be substituted in an effortless and fast way. However, since the columns of the tested structure consist of double-tee profiles, it is clear that no pseudo-dynamic tests could be performed concerning the CHS to through-all I-beam connection.

For this reason, **Chapter 5** is devoted to a brief introduction to the hybrid simulation with dynamic substructuring technique. Such a tool represents a fascinating solution to assess the seismic behaviour of devices when they are part of a more complex structure. This strategy allows the experimental assessment of the considered device while the whole building can be numerically simulated. For such a reason, this approach represents the first step for future developments of this work consisting in evaluating the dynamic response of CHS to through-all I-beam joints through the hybrid simulation with dynamic substructuring technique.

Finally, in **Chapter 6**, the main conclusions are reported.

The topics addressed in this thesis must be framed within broader research projects begun at the University of Salerno a few years ago. Consequently, the author's contribution constitutes only a tiny part of these researches. Therefore, to better place the issues addressed in this thesis in more general fields of study, the following chapters are composed of both the main outcomes of the research projects and the author's personal contributions. In particular, the personal contributions will be summarized at the end of each chapter. For clarity, Table 1 summarizes the topics for which the author’s contribution can be found. These contributions are discussed in much more detail than the bibliographic studies and the results of the previous projects.

Table 1 – Contribution to the thesis

Section or *topic*	**Contribution**
• **Chapter 1**	Bibliographic studies
Study about beam-to-column sub-assemblies	
• **Chapter 2**	
• RBS connection	Results of previous research projects
• CHS to through-all I-beam connection	Personal contribution
• **Chapter 3**	
• FREEDAM and dissipative X-shaped T-stub connections	Results of previous research projects
Study about beam-to-column connections as part of a large-scale structure subjected to dynamic loading	
• **Chapter 4**	
• Pseudo-dynamic tests and numerical simulations	Personal contribution
• **Chapter 5**	
• Hybrid testing method with substructuring technique	Bibliographic studies