TECHNICAL UNIVERSITY OF CONSTRUCTIONS BUCHAREST
FACULTY OF CIVIL, INDUSTRIAL AND AGRICULTURAL CONSTRUCTION

Doctoral Studies, *Specialization: Metal Constructions*

DOCTORAL THESIS
- SUMMARY -

THEORETICAL AND EXPERIMENTAL RESEARCH ON THE DESIGN, MODELING AND BEHAVIOR OF BUCKLING RESTRAINED BRACES

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Foreword

" YOU MUST CONSTANTLY TRY TO CLIMB VERY HIGH IF YOU WANT TO BE ABLE TO SEE VERY FAR."

Constantin Brâncuși

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1. INTRODUCTION

The behavior of the structures during the recent earthquakes highlighted the need to increase the strength and the stable capacity to dissipate energy. Optimization of these mechanical characteristics is necessary in order to maintain global drift and displacement at an acceptable level.

In recent years, one of the solutions studied and then applied has been the use of buckling restrained braces (BRB). In the recent period, many civil or industrial constructions in the USA, Europe, Japan and Taiwan are made with buckling restrained braces. This present paper aims to develop additions to case studies on the design, manufacture and modeling of buckling restrained braces but also to highlight the advantages and disadvantages of using these types of braces by assessing the behavior of buckling restrained braces, subject to static or dynamic stress, based on numerical models and experimental tests. The evaluation of the nonlinear response, the deformation capacity, the distribution of efforts as well as the failure of structural systems, which use such braces, are information of particular interest to structural design engineers.

The idea of using metal devices with high energy dissipation capacity, integrated in the structures, has appeared for more than 30 years. Early research in the field of seismic protection of structures considered torsion beams, bent beams and other structural mechanisms as the basis for induced energy dissipation devices in bends subjected to bending or axial forces. Subsequently, a wide range of efficient energy dissipation devices was proposed. The motivation for using these devices is to achieve a uniform plasticization distributed throughout the material, and to avoid local deformations, which will quickly lead to failure of the devices due to fatigue after a small number of loading-unloading cycles. [1]

The concept of buckling-restrained brace was developed in Japan in the late 1980's and in the United States after the Northridge earthquake in 1994 and is now a displacement-dependent lateral takeover solution accepted and regulated by current standards. The need for economic solutions that provide adequate strength for new structures is now growing in Europe and is accelerating the use of buckling-restrained braces.

Buckling-restrained braces (BRB) are composed of a ductile steel core inside an outer tube with the role of preventing buckling (Fig.1.1). The core and housing are disconnected by a non-stick material to prevent interaction between them.

The following components are distinguished in the cross-section of the buckling-restrained braces:

-steel core

- non-adhesive material

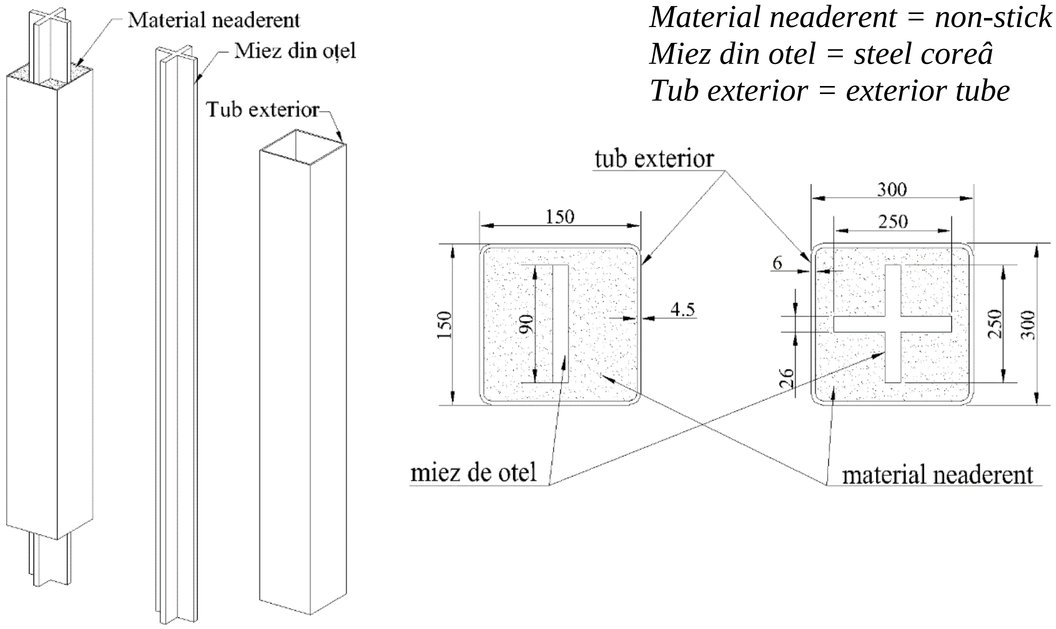
-external tube (pipe)

The types of commonly used buckling-restrained braces (cross section) are shown in Fig. 1.

The layer of non-adhesive material disconnects the outer tube from the steel core. Therefore, the axial force of the braces is transmitted only by means of the steel core, while the outer tube (due to its stiffness at bending) ensures adequate lateral support against bending by bending the core.

The steel core must withstand the full axial force developed in the bracing. The cross section at buckling-restrained braces may be significantly smaller than that of ordinary braces, as its performance is not limited by buckling. Along the core there are three areas: the middle part that is plasticized (yielding length) and the rigid ends that are not plasticized. Enlarging and usually strengthening them ensures the behavior of the ends in the elastic field, and thus plasticization will develop in the middle of the core. Such a bracing configuration provides a high degree of confidence and a good prediction of the behavior and failure of the element.

The outer casing is usually made of steel tubes filled with concrete or other materials that do not adhere to the metal core. The outer tube must be designed so as to prevent side buckling of the steel core.

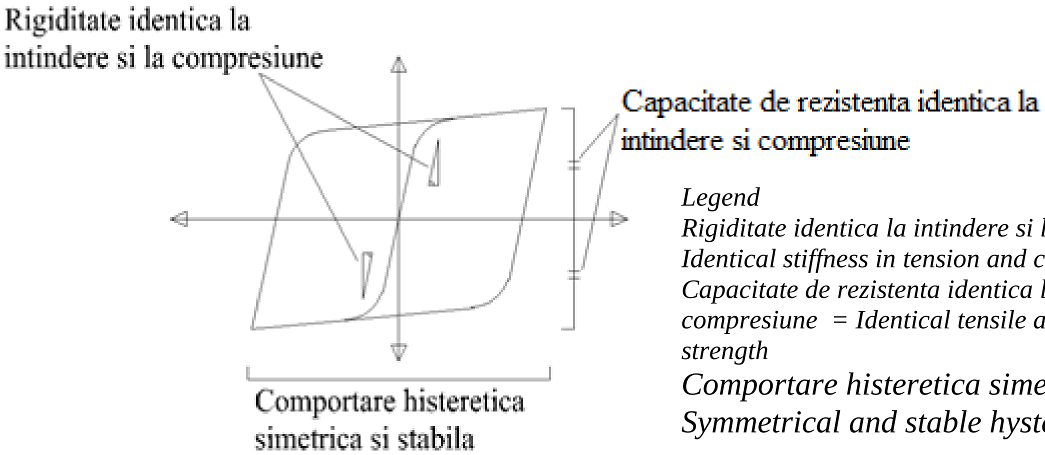


Legend:
Material neaderent = non-stick material
Miez din otel = steel coreâ
Tub exterior = exterior tube

Fig. 1 - *Buckling-restrained brace components and the usual types of BRB sections [49]*

Difficulties in estimating the performance of centrally braced frames, due to the difference in capacity for compression and stretching braces and due to the degradation of resistance due to cyclic loads, have led to research aimed at creating a brace with more stable elastic-plastic behavior. To this end, the idea of preventing the buckling of the braces through an external system was reached.

Frames equipped with buckling-restrained brace have a high capacity for absorbing seismic energy, the hysteretic behavior of these frames being symmetrical and stable in the plastic field (Fig.2).



Legend
Rigiditate identica la intindere si la compresiune = Identical stiffness in tension and compression
Capacitate de rezistenta identica la intindere si compresiune = Identical tensile and compression strength
Comportare histeretica simetrica si stabile = Symmetrical and stable hysteretic behavior

Fig. 2- *Behavior of buckling-restrained braces [49]*

BRB head restraints can be of several types, each with specific advantages and disadvantages:

- bolted joints - the advantage is the reduction of the 2nd order moment induced by the level displacements but also the increase of the effective length of the steel core, thus achieving the reduction of the specific deformation.

- the disadvantage is the low mounting tolerance

This type of grip insulates the dissipating bar from bending moments and shear forces in the structure.

● welded / screw fasteners - the advantage of this model is the short implementation time
- the disadvantage is the 2^{nd} order moments at the level of joints and elements

With the advent and development of the finite element method, many of the experimental tests are optimized by using this method in determining the behavior of some structural elements or systems. The experience and knowledge gained over time, based on numerous analytical models validated on the basis of experimental tests, performed on buckling-restrained braces, have led to the improvement of modeling techniques and calculation tools (programs), which can currently now provide results with a high degree of confidence.

The accuracy of the results depends on the complexity of the models used. Finite elements can be used to evaluate the behavior of BRBs, which can simulate complex phenomena such as the contact between concrete and steel, the phenomenon of crushing concrete, buckling of steel bars under compression forces.

Structures are subjected to high cyclical forces during an earthquake. Buckling-restrained braces are used to increase the strength of the frames of the structures through energy dissipation and non-linear behavior. Testing and evaluation of buckling-restrained braces are necessary for the design and quality control of the execution. Although laboratory experiments lead to results consistent with the actual behavior of these seismic devices, these tests require significant financial resources and also extend the project's development programs.

The research of the devices has two important purposes: to analyze the hysteretic behavior of BRB (additional compressive strength, friction between the steel core and the buckling prevention system, the distribution of plastic deformations) and secondly, to find a numerical model as close as possible to actual behavior to replace and reduce the number of expensive experimental tests.

During an earthquake, BRBs must withstand cyclic forces and large plastic deformations. Therefore, it is important to adequately describe the cyclic behavior of the material in the calculation models for buckling-restrained braces.

Ordinary steel behaves differently under cyclic loading and monotonous loading, as several experiments have shown [22]. When the friction between the crystals of the material decreases, the Bauschinger effect reaches a state of saturation and the area closed by the hysteresis loop decreases more and more.

2. CONTENT OF THE DOCTORAL THESIS

The paper is structured in 6 chapters as follows:

Chapter 1 – Introduction

The first chapter is introductory, establishes the field in which the doctoral thesis falls and presents the objectives of the thesis. Thus, there are considerations regarding the composition and usefulness of buckling-restrained brace but also the importance of improving the behavior of structures subjected to seismic actions. In recent years, the concept of seismic response control has been developed in order to limit the damage caused by earthquakes and to optimize execution costs. This control is performed by introducing seismic energy dissipation devices (dissipators) into the structure. Since in Romania these systems are not widely used, I need recommendations regarding their implementation in the specific seismic conditions of our country.

Chapter 2 - The Current State of Use of Buckling-Restrained Braces in Romania and In the World

The second chapter presents the current state of use of BRB-type seismic energy dissipation devices internationally and details of the execution used in the manufacture of these devices. Internationally, the concern for the use of BRBs began in the 1970s. In 1973, Wakayabashi and his entire research team conducted a comprehensive study of all BRB components, but BRB devices began to be widely used in 1987. At national level, the designers' reservations regarding the use of BRB type seismic energy dissipators come from the lack of models and calculation methods of the structures equipped with these types of devices, correlated with the Romanian design codes.

Chapter 3 - Theoretical Elements on Buckling-Restrained Braces

In the first part of the chapter, the calculation principles and models used in the design of the buckling-restrained brace are presented. The second part of the chapter presents the comparative analysis of 6 models of structures that aim to highlight certain characteristics favorable or unfavorable to the BRB braces used. The BRB system was introduced either in the form of an inverted V or in the form of an X in 2 levels attached to the articulated ends. Nonlinear static analysis was applied for 6 15-level office buildings located in Bucharest. Due to a significant contribution of BRB systems to the seismic behavior of structures, the idea of completing the theoretical study with an experimental study emerged. A frame with inverted BRB V-braces was isolated for experimental testing. The design of the buckling-restrained brace made in this chapter provided input for the experimental tests described in Chapter 4.

Chapter 4 - Description of the Experimental Research Framework

The experimental program described in this chapter contributes to the research of buckling-restrained devices in Romania. Based on the calculations performed in Chapter 3, 3 BRB prototypes were designed which were subsequently executed and tested experimentally at 1: 1 scale (fig.3.) in the CERS laboratory (Seismic Risk Assessment Research Center) within the Technical University of Bucharest constructions. The loading regime of the BRB elements in the laboratory was of ascending cyclic type. The prototypes are made of a flat steel strip inserted in a steel tube later filled with concrete. Three different types of materials were used to prevent friction between the steel core and the concrete. Decofrol for the BRB-1 prototype, PTFE plates for the BRB-2 prototype and for the BRB-3 prototype a "sheath" of Teflon sheets was used as a non-stick material. This chapter also describes the processes for performing buckling-restrained braces and experimental validation of the results obtained from prototype testing.

Chapter 5 - Results of the Experimental Research

This chapter presents the results obtained experimentally for each prototype tested. They showed that the BRB elements, made by simple means of insulating the core of the concrete filler, did not prove their functionality. Even if deficiencies were found during the tests and some components of the prototypes had to be redesigned, the results can be considered encouraging due to a significant improvement in their behavior after the repairs were performed.

Chapter 6 - General Conclusions and Personal Contributions

This chapter summarizes the conclusions, personal contributions and future research directions on the topic of the thesis.

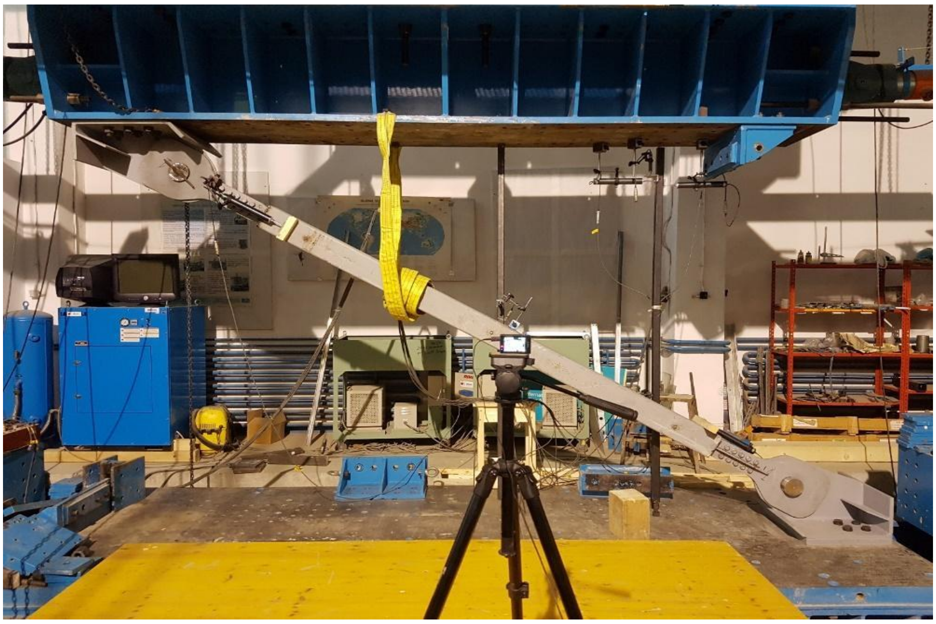


Fig.3 – Testing prototypes of buckling-restrained braces

3. *GENERAL CONCLUSIONS AND PERSONAL CONTRIBUTIONS*

3.1 *Conclusions*

The experimental program described is a supplement to the studies performed on buckling-restrained braces. The paper describes the design process of 3 BRB prototypes, the execution of prototypes, their testing and presents the analysis of the results of the testing program. The 3 BRB prototypes were calculated for the models of structures with inverted V bracing.

Chapter 3 identified advantages and disadvantages for 6 structures equipped with classical bracing and BRBs using nonlinear analysis at geometric and element level and presented the conclusions and observations resulting from the study. The structural response was analyzed in terms of the following parameters: steel consumption, displacement at the top and the stages in which the plastic joints of the dissipative structural elements were located according to the performance levels regulated in Romania. The study performed on the 6 models with and without dissipative bars (in classic solution with X and V inverted braces) led to the following conclusions:

- - Internationally, the concern about the use of BRB-type seismic energy dissipation devices is old (1980s), while at the national level the use of dissipators has started recently, and the trend is to apply them as widely as possible.

- for the same amount of dissipated energy, the structures with BRBs have higher displacements

- in the case of structures with BRB, after the action of the code earthquake, the only elements that need to be replaced are the BRBs, the other elements having minimal incursions in the inelastic field. BRBs can be replaced easily and quickly, saving significant time and money.

- for the solution with inverted X and V braces without BRB, the inelastic incursions are insignificant so that both the beams and the braces should be replaced after the action of the code earthquake. This is a technically difficult intervention, expensive and practically impossible.

- Classically braced structures (without BRB) are stiffer than those with BRB as long as the compressed bars do not buckle, designed for strength and rigidity criteria.

- steel consumption decreases by approx. 12% in the case of structures designed with high ductility both for structures equipped with classical bracing and for structures equipped with BRB compared to the consumption of structures designed with medium ductility.

- the structure braced with BRB in X and designed so as to satisfy the requirement of high ductility is more expensive by approx. 2% than the structure without BRB.

- a problem studied intensely lately consists in the analysis of the optimal location of the dissipators in the structure, using a small number of devices. To reduce costs, upper third BRBs that have not had a foray into the plastic field can be replaced with conventional braces that can work in the elastic field.

- the results obtained following the analysis of the parameters show that the models with diagonals arranged in inverted V have smaller efforts and displacements under the action of the code earthquake compared to the models with diagonals arranged in X on 2 levels.

- by comparing the ratio between the peak travel and the basic shear force (for models with and without BRB bracing) it can be concluded that braced models with BRB can absorb more energy during the action of the code earthquake.

- from the comparative study of the models and from the analysis of the results, it can be concluded that in the case of code earthquakes, the models equipped with BRB have better performances than the models equipped with classic bracing. BRB devices reduce the effort of computational models and ensure the stability of the building.

This paper is a useful documentation for the development of recommendations for the design, manufacture and modeling of buckling-restrained braces but also highlights the advantages and disadvantages of using these types of braces by assessing the behavior of buckling-restrained braces, subject to static or dynamic stresses, based on numerical models and experimental tests. The evaluation of the nonlinear response, the deformation capacity, the distribution of the efforts as well as the way of yielding these structural systems, are information of special interest for the engineers designing structures. The processing of numerical experiments on structures equipped with BRBs highlighted the advantages and disadvantages of introducing these devices to multilayered metal structures.

The study performed on the 3 prototypes of dissipative bars led to the following conclusions:

- the results of the tests carried out have shown that rigorous control of the design of the dissipative bars must be ensured. The execution of these anti-seismic devices is not recommended on site but only in factory conditions where the uninterrupted technical control of the execution will be performed. Quality control will also be performed at the ends of the metal tube in sensitive areas, where it is possible to lose local stability by side buckling of the outer area of the metal core. The execution will comply with the provisions of the standards and norms in force but also with the technical instructions elaborated by the designer of the buckling-restrained braces.

- for all the tests carried out, the failure occurred at the lower end of the braces relative to the pouring position, which is largely due to the poor behavior of the filling mortar. The failure occurred in all 3 specimens by losing the local stability of the steel core outside its plan. Therefore, a more efficient vibration system of the mortar must be made for the lower end of the BRBs relative to the pouring position.

- the critical area of the steel core is in the area inside the pipe, next to the reinforced area of the steel core, the area where the buckling failure occurred outside the plane of the steel core.

- ensuring a lateral support against the loss of local stability for the steel core in the end areas of the metal outer tube by providing thicker "covers" welded by it, during cyclic loading, significantly improves the overall behavior of the BRB.

- a significant improvement in the behavior of the prototypes was observed by replacing the plates (caps), with a thickness of 3 mm from the ends of the pipe, with plates (caps) with a thickness of 10 mm. The 3mm plates were expelled from the concrete to the BRB-1 and BRB-2 prototypes but not to the BRB-3 prototype where 10mm thick end plates (caps) were used. It is also recommended to use end plates in contact with the steel core (without blanks) so that they are fixed side supports against side buckling failure.

- an elastic behavior of the prototypes was observed during the first two loading cycles. The yield of BRB prototypes started in cycles 3 and 4 at about 20% of the floor drift.

- a new cover for BRBs must be designed and tested. The connection of the cap to the tube should eliminate some of the problems that were observed with the BRB prototypes in the laboratory tests. It is recommended that these caps be rigid enough to prevent buckling of the steel core in the end areas.

3.2 *Personal Contributions*

The main personal contributions to the field studied resulting from this paper are the following:

- This Thesis, a pioneering work in Romania, presents the way in which prototypes of buckling-restrained braces were made and tested (from own funds and sponsorships). This is one of the first doctoral theses in Romania to study in detail this type of restrained buckling devices.

- Carrying out a documentary study on the use of buckling-restrained braces at national and international level.

- I have exemplified, adapted and applied according to the standards in force, a design precedent for multi-layered metal structures equipped with buckling-restrained braces.

- Analysis of several case studies that highlighted the procedure for sizing buckling-restrained braces for different configurations of bracing.

- A buckling-restrained brace design procedure was performed.

- A procedure has been carried out for the design of buckling-restrained braces and a system for the prevention of buckling.

- I described the experimental qualification procedure of buckling-restrained braces for the type of BRBs tested in this thesis.

- I manufactured and tested 3 prototypes of buckling-restrained braces.

- I have proposed a series of recommendations regarding the design and execution of buckling-restrained braces.

- Experimental results have been encouraging for more complex future research and subsequent experimental testing with different ways to prevent friction between the steel core and mortar and to seal the ends of the outer metal tube so as to prevent the expulsion of the mortar and the weakening of the section strength in that area.

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