

Article

Experimental Analysis of Watertightness Performance of Interfaces between Masonry and Steel Structures Subjected to Accelerated Aging

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Abstract: Steel buildings often experience failure at the interfaces between their vertical exterior enclosure systems (VEESs) and structural elements. This phenomenon generates various pathological manifestations in steel buildings, resulting in the precocious decay of the structure and the diminishment of its service life. The treatment of these interfaces is essential for ensuring their proper performance and watertightness, and to protect the durability of the steel structure. This paper proposes a method for treating common interface joints between masonry and steel structures with the application of an EPDM (ethylene propylene diene monomer) elastomer membrane. The main goal of this building technique is to ensure the durability and watertightness of the interface's joints when they are subjected to aging triggered by heat exposure and thermal shock. The experimental models tested consisted of a steel frame and a conventional masonry vertical enclosure system with ceramic blocks plastered with cement mortar. The models were subjected to ten cycles of heat exposure and thermal shock for the purpose of simulating accelerated aging, followed by a watertightness experiment that simulated the action of both rain and wind pressure. The interfaces between masonry and the steel structure proposed in this study allowed adequate differential movements between the parts, without damage to joints and masonry. Only small cracks were observed in the outer test region of all of the interfaces tested. In the regions of the joints treated with the EPDM membrane, no alterations were visible to the naked eye. During the cycles of the heat exposure and thermal shock test, the maximum relative horizontal displacements observed in the joints were 0.743 mm for vertical joints and 0.230 mm for horizontal joints, indicating the accurate reproduction of the behavior expected from an untied interface. The results obtained in the previously mentioned watertightness test showed that no humidity stains were found on the inner face of any of the specimens, even after the continuous application of a pneumatic pressure of 400 Pa for eight hours. Therefore, the results indicated satisfactory performance in terms of durability and watertightness in all evaluated cases, indicating that the application of an EPDM membrane can be effective in preventing water leaks in the interfaces between masonry and steel elements, thus contributing to ensuring the steel structure's durability.



Citation: Bhering, A.d.F.; Franco, R.N.; Santos, M.A.d.; Sathler, L.d.M.; Pedroti, L.G.; Varum, H.; Veríssimo, G.d.S.; Paes, J.L.R. Experimental Analysis of Watertightness Performance of Interfaces between Masonry and Steel Structures Subjected to Accelerated Aging. *Buildings* **2023**, *13*, 2123. <https://doi.org/10.3390/buildings13092123>

Academic Editor: Daxu Zhang

Received: 26 July 2023

Revised: 13 August 2023

Accepted: 19 August 2023

Published: 22 August 2023



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Keywords: steel structure; masonry; interfaces; watertightness; durability

1. Introduction

Serviceability limit states (SLS) are generally associated with a non-catastrophic event and serve as a parameter for assessing the quality of a structure. Exceeding an SLS means that the structure is compromised due to damage to non-structural elements or

unpleasantness being caused to its occupants [1,2]. Such consequences are associated with economic factors, while ultimate limit states are related to the structure's and its users' safety.

When designing steel structures, it is necessary to verify the SLS of excessive horizontal displacements. These displacements interfere in non-structural elements and in interfaces between steel and masonry. Currently, a series of technical and economical requirements motivate the search for more sustainable structures with lower material consumption that can lead to more displaceable structures. As a consequence, some authors have been investigating models that are more precise than those presented in current standards for the design of the structural elements comprising steel frames [3].

Horizontal and thermal actions can cause damage to masonry walls and to the interfaces between masonry and steel structure. Lately, a number of innovative solutions aimed at ensuring the integrity of masonry walls by employing carbon fiber strips have been widely employed, whether or not there is any seismic activity in the region. The effectiveness of this technique essentially depends on the adherence of the strips to the masonry surface. This subject has been investigated by several authors, with an emphasis on the detachment of the strips [4]. However, there are still very few solutions that ensure good performance regarding the durability and watertightness of the interfaces between the masonry and the steel structures that form vertical exterior enclosure systems (VEESs).

Vertical exterior enclosure systems (VEESs) play an important role in buildings, and their design must take into consideration the particular characteristics of the structural system to which they will be connected.

All around the world, VEESs in ceramic block masonry remain a common choice for multi-story steel structure buildings. In these systems, the interfaces between masonry and steel structures exert a great influence on the VEESs' performance in relation to the structure's watertightness and durability.

It has been noted that, when traditional solutions in ceramic block masonry are employed in steel structures without proper interface design, several types of pathological manifestations are likely to occur, such as cracks in the masonry, corrosion of the steel structure, excessive displacements, and rainwater infiltrations [5,6]. This results in functional and aesthetic damage, reduced project service life, and economic losses.

In steel constructions, the presence of large spans and the existence of interfaces between masonry and structure require an enclosure system capable of withstanding structural displacements while simultaneously impeding rainwater infiltrations on the building's façades without conflicting with its architecture, structure, and installations.

Design criteria and concepts have not kept pace with the evolution of the products and systems applied in the construction of building enclosures [7]. Some previous studies have shown that current design recommendations for façade panel systems with open joints may not be ideal for preventing water infiltration [8]. Consequently, the number of pathological manifestations has been increasing, resulting in user dissatisfaction.

Stover et al. [8] evaluated the watertightness of different design solutions for horizontal joints in façade panels employing different types of aluminum profiles and EPDM (ethylene propylene diene monomer) strips. The experimental models were subjected to a system that simulated rain. The authors concluded that the design solutions evaluated performed differently for the different types of panels, making it difficult to draw general conclusions.

The building's exterior must be protected against the elements to prevent wind-driven rain from entering the structure, since water penetration often causes humidity problems in addition to structural decay [9,10].

Linden and Boscche [11] presented a broad review about the rate of rainwater infiltration into walls, highlighting the importance of the subject in evaluating the long-term performance of wall assemblies. Due to the nature of the rainwater infiltration phenomenon, it is difficult to predict the amount of water that will infiltrate into a wall. However, the authors highlight that laboratory and field tests can provide important information that could allow for more accurate predictions of infiltration rates.

According to Pérez-Bella et al. [12] the joint action of wind-driven rain and wind pressure is the main cause of moisture penetration on the exterior of buildings, resulting in several durability and habitability problems. In the area of durability, the main issues are erosion, corrosion, frost attack, salt crystallization, surface soiling and discoloration, loss of adherence, deformations, cracking, and falling materials [13–15].

The majority of the pathological problems found in steel structures begin in the conception stage of basic and executive projects in engineering and architecture. Interfaces between the masonry sealing system and the steel structure are often designed incorrectly, and the construction-related details specified for their treatment are often inadequate. The interfaces between the masonry and the steel structure employed in masonry VEESs in Brazil comprise horizontal and vertical joints that are usually treated with sealants, following practices recommended in technical manuals such as [7,16]. However, the history of many buildings indicates that this solution does not have adequate performance.

According to Liden and Boscche [17], there has been an increase in the employment of pre-compressed foam sealing tapes for sealing joints between building envelope components. There is little to no information regarding the parameters that affect the durability of these tapes under driving rain conditions. It was also noted that water leakages can be expected at relatively low pressures.

For this reason, it is necessary to seek construction-related solutions that can guarantee a good interface performance level regarding watertightness and fulfill durability criteria. The durability and watertightness performance of interfaces must be assessed through experiments in order to improve these construction-related solutions.

This paper proposes a treatment for the joints at the interfaces between masonry and steel structures using an EPDM (ethylene propylene diene monomer) elastomer membrane. The joint specifications presented in this work were developed by the authors after a thorough evaluation of various solutions. The main goal of this building technique is to ensure the durability and watertightness of the interface's joints when these are subjected to aging triggered by heat exposure and thermal shock.

2. Background

2.1. Vertical Masonry Enclosure Systems Employed in Brazil

Vertical enclosure systems greatly influence a building's durability performance. These systems are responsible for the volumetry and compartmentalization of a building's spaces, functioning as a protective barrier for users against external environmental agents and directly affecting thermal comfort. In Brazil, vertical masonry enclosure systems made of thin ceramic blocks are often employed in steel constructions. The choice of such enclosure systems is justified mainly due to the tropical climate and the systems' low cost compared to other solutions, as well as the fact that they do not require skilled labor.

In order to allow the systematization of projects employing vertical masonry enclosure systems in steel structures, we propose the following classification, which is based on three parameters: masonry leaf continuity, masonry placement, and the stiffness of the joints between masonry and steel structure, as shown in Figure 1.

According to Laska [18], masonry and steel structures are in constant movement. Both undergo volumetric changes due to temperature variations and deformations caused by static or dynamic loads. The magnitude of these volumetric changes depends on the physical properties of both masonry and steel, which behave differently. As a result, differential movements occur when the two materials are used together. Steel is a good thermal conductor, and is quickly affected by the external environment's temperature. Since the steel's coefficient of thermal expansion is considerably higher than that of masonry, differential movements between the two are inevitable.

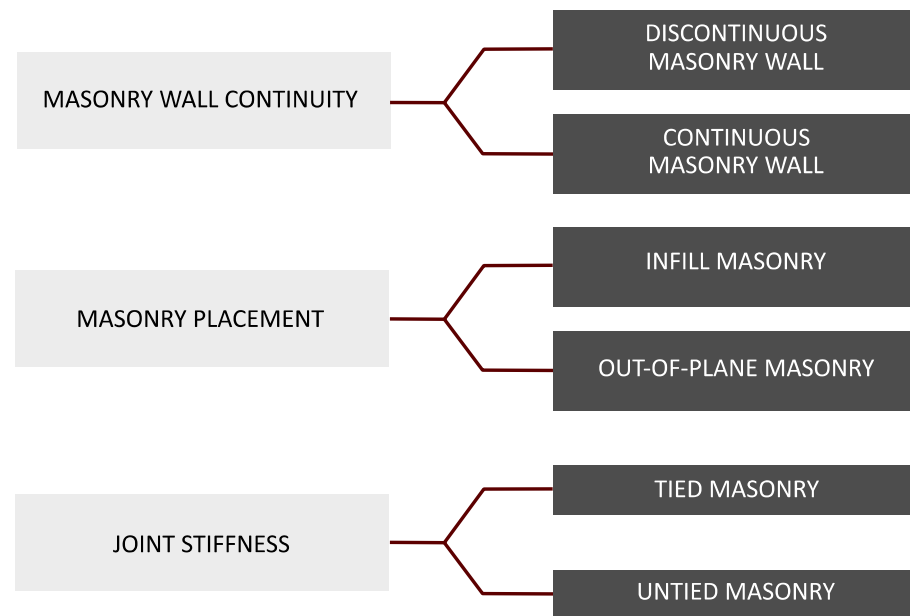


Figure 1. Vertical masonry enclosure system classification.

2.2. Interface Characteristic and Associated Pathological Problems

Due to construction considerations, vertical masonry enclosure systems that interface with steel structures possess horizontal and vertical joints. These joints must be treated adequately in order to avoid water leaks in the interfaces between the steel and the masonry.

In several places, masonry enclosure systems comprised of infill of discontinuous walls are common in multistory steel-structure buildings. In this configuration, masonry leaves are often divided by beams, and it is thus necessary to treat the joints between the masonry and steel elements.

According to Hutchinson et al. [9], joints represent vital parts of buildings, and must be designed, constructed, and sealed in a professional manner, so that they do not become weak links in the building's structural performance. Therefore, the materials for the treatment of joints play an important role in modern construction, as they must be capable of adhering to a wide variety of substrates, accommodating multidirectional movements, resisting damaging environmental factors, and maintaining adequate aesthetic qualities, while also lasting as long as possible.

Some technical manuals [7,16] present construction specifications for the interfaces of masonry enclosure systems that recommend the joints be treated with polyurethane sealants. Based on the observation of several construction works in Brazil, it can be affirmed that, in many cases, joints are not treated at all, while joints treated with polyurethane sealants often undergo precocious watertightness failure. These failures are usually related to the inadequate application of the sealant or to the non-replacement of this material at the end of its service life.

Recent studies have shown that the most common causes of pathological manifestations in steel-structure constructions are related to the vertical enclosure system, especially when the treatment of the interface between masonry and steel elements is deficient or absent [5,6].

2.3. Accelerated Aging and Watertightness Performance Assessment

According to Bochen [19], the durability of a building's materials and components when exposed to climatic agents is essential in ensuring their service life. Durability is usually understood as describing the time for which the user's requirements are met. In this context, comparative studies of long-term aging processes, under real conditions, and of short-term accelerated aging processes, under simulated conditions, are very useful

for the assessment of durability. As highlighted by Asphaug et al. [20], the process of accelerated artificial aging requires materials to be subjected to climatic factors similar to those experienced during a building's service life, but at a high intensity over a shorter period. This allows the vulnerability of building products or façade systems to be tested within a reasonable time.

Over time, several studies regarding the decay of materials employed in building joints have been conducted with the purpose of defining experimental methods capable of evaluating losses related to the physical or chemical characteristics of these materials, as well as in order to evaluate their performance in the long term [21]. However, less attention has been given to the understanding of the consequences of sealing failures along the joints, especially in relation to airtightness and watertightness. Deficiencies can be caused by failures in design, materials, or application.

Ding and Liu [22] tested certain types of sealant under the effects of heat, at a temperature of 80 °C, as well as separately under ultraviolet radiation (300 W), in a chamber equipped with UVA-340 nm lamps, in which the samples' surface was kept at 50 °C. Both experiments were conducted for the purpose of testing samples under the effects of weathering for 5000 h. They observed that, in polyurethane-based sealants subjected to over 3000 h of exposure, the only effect was a gradual yellowing under ultraviolet radiation, with no appearance of cracks, while samples subjected to thermal aging displayed a shrinking of their volume. The authors concluded that a reasonable period of accelerated weathering aimed at inducing evident changes in the sealant's properties should span at least 5000 h. Furthermore, they also observed that UV radiation accelerated changes to the sealant's appearance, while heat accelerated the degradation of its mechanical properties. A method for calculating the aging rate was also presented in [23].

According to Gričutė et al. [24], natural and accelerated aging experiments are important for determining the aging characteristics of materials and predicting their real durability. Many different accelerated aging tests and evaluations have been proposed in order to predict and compare the durability of several types of materials for exterior trim. Among their conclusions, these authors highlight that, in most cases, accelerated aging cycles underestimate the specificities of the country's geographical location and its predominant climate, preventing these cycles from being applied in all climate zones.

According to several authors [25–29], recent research has revealed several inconsistencies in watertightness experiments regarding the proper representation of different operating conditions, different building types, and different building locations.

In Brazil, the heat action and thermal shock experiment is established in ABNT NBR 15.575-4:2021 [30], and is aimed at evaluating the VEESs' behavior regarding damage and displacement when subjected to successive cycles of heating and cooling with water. This experiment allows the simulation of stress caused by variations in temperature and humidity associated with the action of rain on heated sealing elements, resembling what occurs during the service life of a building that is exposed to the elements. The watertightness experiment is also established in the ABNT NBR 15.575-4:2021 [30], and is aimed at evaluating water penetration through the VEES. This experiment allows the verification of watertightness performance against rainwater or other moisture sources, taking into consideration the joint action of wind pressure.

On an international level, many authors [26,28,29] have recently developed works aimed at perfecting the representation of phenomena that affect the durability and watertightness performance of vertical enclosure systems. The guidelines that deal with the evaluation of a vertical enclosure system's performance in a building include experiments that, for the most part, only offer a qualitative assessment of phenomena.

Although they are not specifically aimed at the evaluation of interfaces between masonry and steel structures, the employment of the heat exposure and thermal shock test along with the watertightness test enables the deliberate accelerated aging of interface joints between masonry and steel structures and the assessment of water penetration through the VEES.

3. Materials and Methods

The study was conducted in the following steps:

1. Design and construction of an experimental model with interfaces commonly employed in masonry vertical exterior enclosure systems (VEES) for steel structures;
2. Treatment of joints with an EPDM elastomer membrane;
3. Heat exposure and thermal shock test;
4. Painting of the experimental model;
5. Watertightness test.

3.1. Experimental Model

The experimental model comprised a steel frame filled with a ceramic block masonry enclosure wall, plastered with cement mortar. Two samples were built (E1 and E2) with the same characteristics, so that the experiment could be carried out twice. In the experimental model, three common interfaces between masonry and steel structure were represented.

The experimental model was subjected exclusively to the thermal actions specified in the heat exposure and thermal shock test. No other action was introduced into the model, especially actions capable of causing horizontal displacements in the structure, since the goal was to reproduce the functioning state of a building in regions that are not subject to seismic activity.

Figure 2 displays a schematic of the experimental model indicating the type and location of the common interfaces represented. The region contained in the smaller rectangle, represented with dashed lines, corresponds to the watertightness test, while the region contained in the larger rectangle, with continuous lines, corresponds to the heat exposure and thermal shock test.

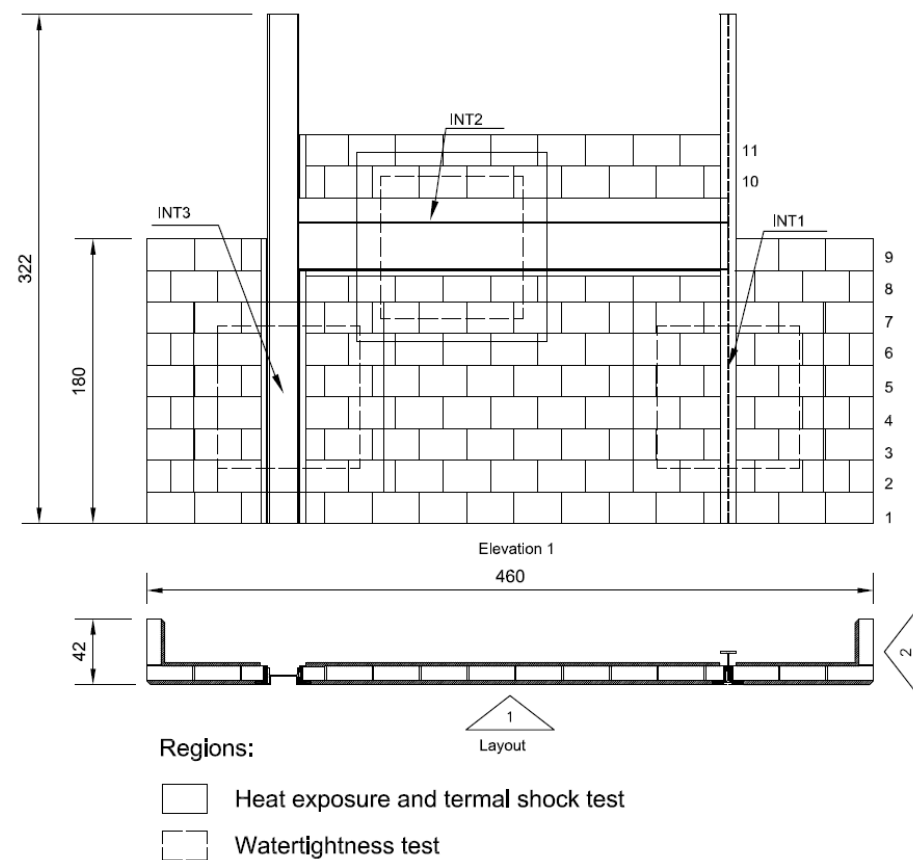


Figure 2. Experimental model schematics with indications of common interfaces.

The experimental models are identified in the form INT#-JV#-E#, where INT represents the interface type, J the joint type (H—horizontal; V—vertical), E the sample, and # the sequential numbering.

Interface INT1 corresponds to an interface between the masonry and the web of a steel column. This interface contains two identical vertical joints (JV1 and JV2) ranging from the column's base to the steel beam. A sheet of EPS was inserted between the masonry and the steel column, allowing the wall to move apart from the steel frame. A pair of angles was welded to the column's web with intermittent fillets in order to prevent the wall from moving out of plane. Figures 3 and 4 display the specifications for interface INT1.

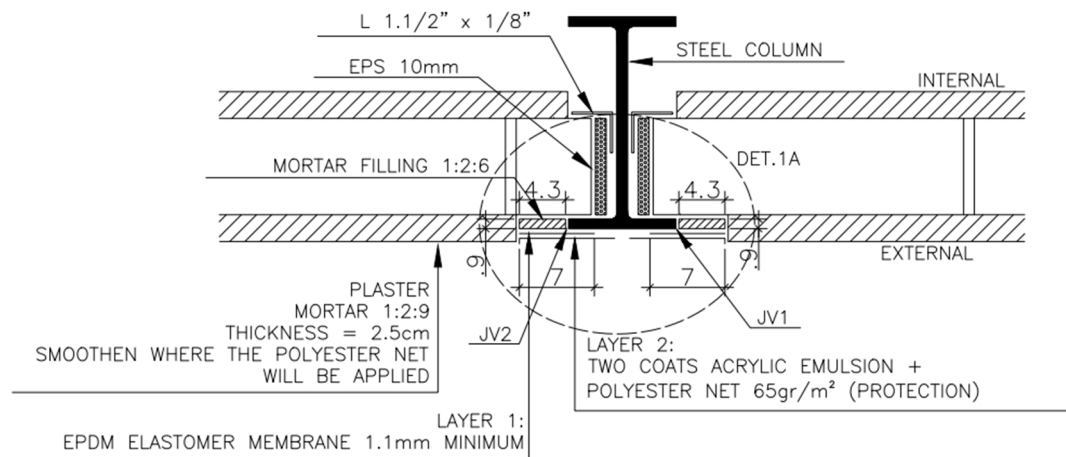


Figure 3. Specifications for interface INT1 from the experimental model.

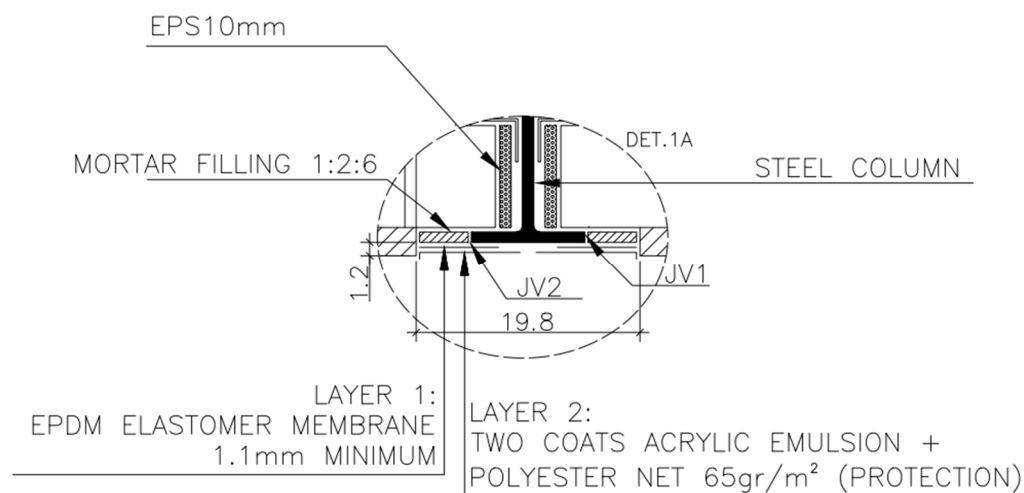


Figure 4. Detail 1A for interface INT1.

Interface INT2 contains three horizontal joints, the first being between the masonry and the concrete slab (JH1), the second being between the concrete slab and the steel beam (JH2), and the third being between the masonry and the steel beam (JH3). This interface's specifications are displayed in Figures 5–7.

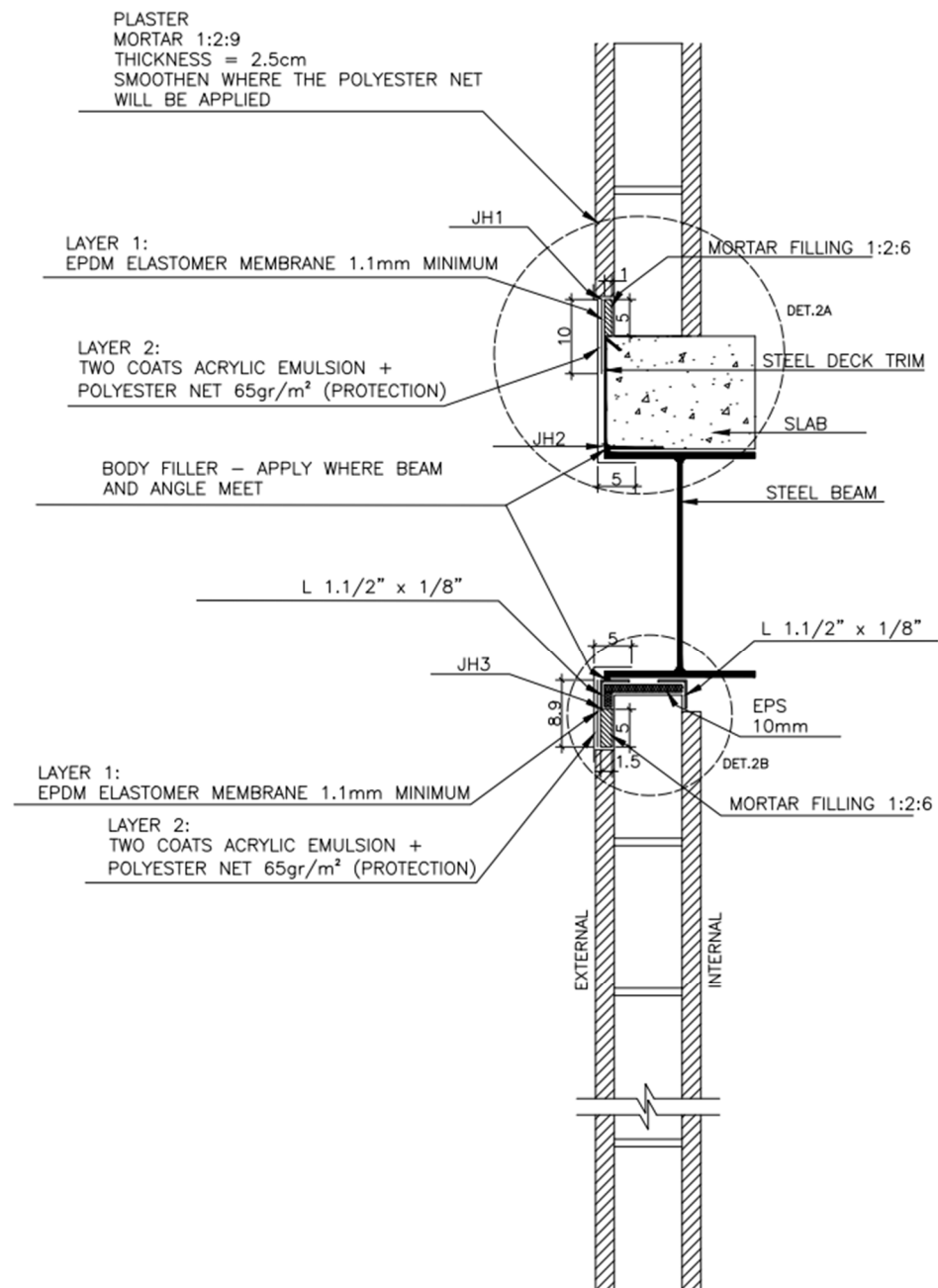


Figure 5. Specifications for interface INT2 from the experimental model.

Interface INT3 corresponds to an interface between masonry and the flange of a steel column. This interface contains two identical vertical joints (JV1 and JV2) ranging from the column's base to the steel beam. A sheet of EPS was inserted between the masonry and the flange, allowing the wall to move apart from the steel frame. A pair of angles was welded to the column's flange with intermittent fillets in order to prevent the wall from moving out of plane. Figures 8 and 9 display the specifications for interface INT3.

For each interface represented in the experimental model, test equipment for heat exposure, thermal shock, and watertightness were placed so that they could reach all of the joints in the interface. This allows the assessment of the influence of construction-related aspects and of the interaction between the joints of each interface.

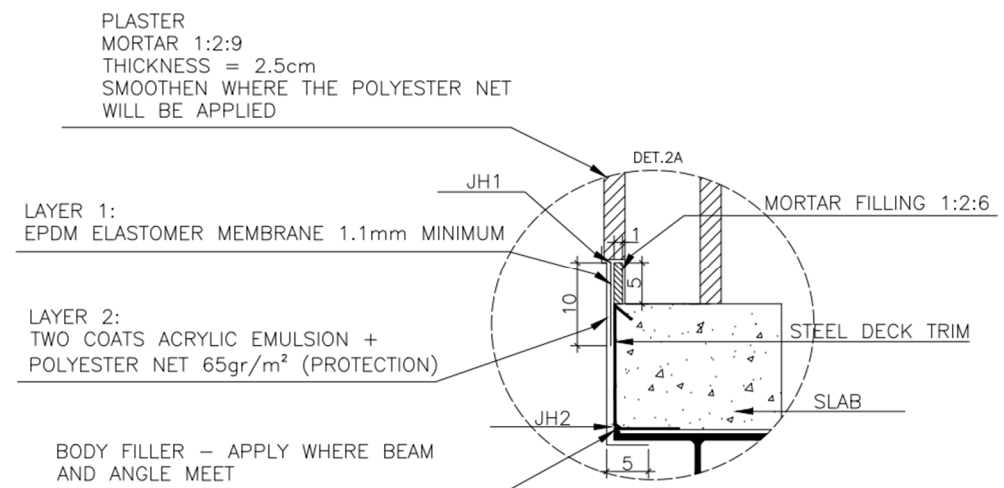


Figure 6. Detail 2A for interface INT2.

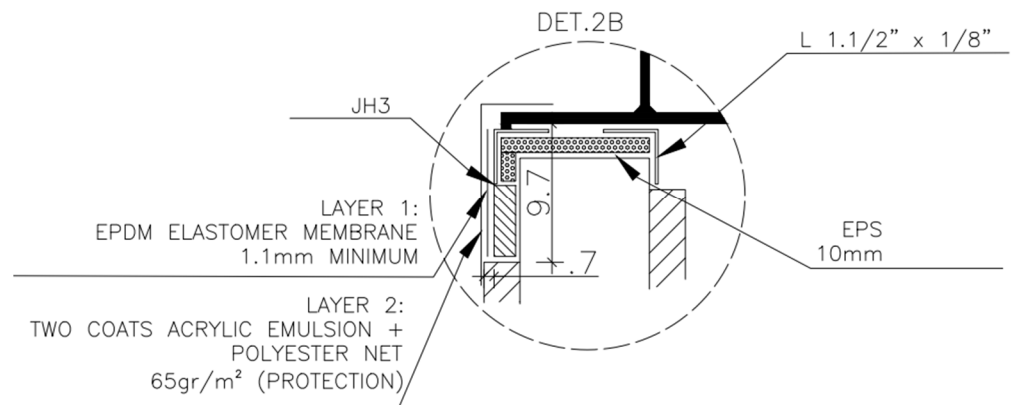


Figure 7. Detail 2B for interface INT2.

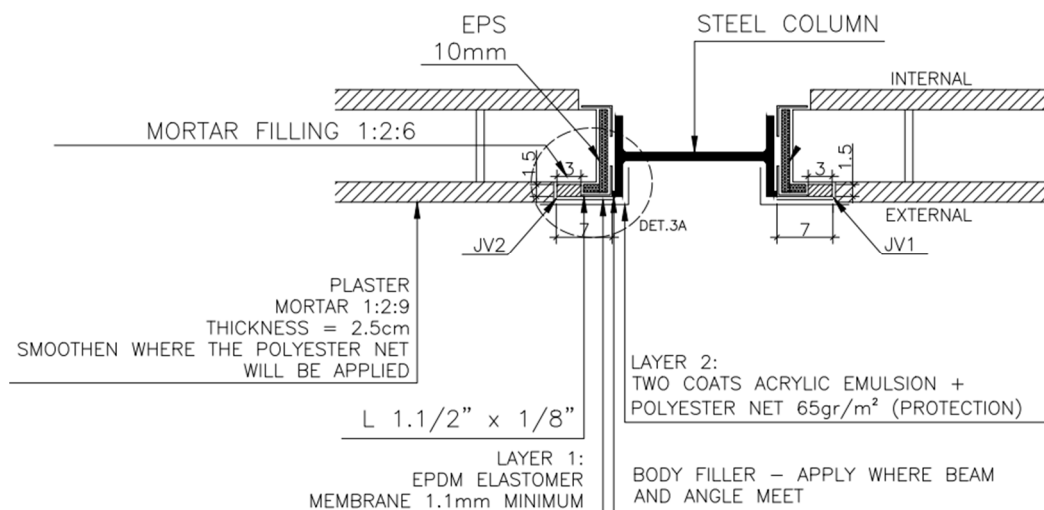


Figure 8. Specifications for interface INT3 from the experimental model.

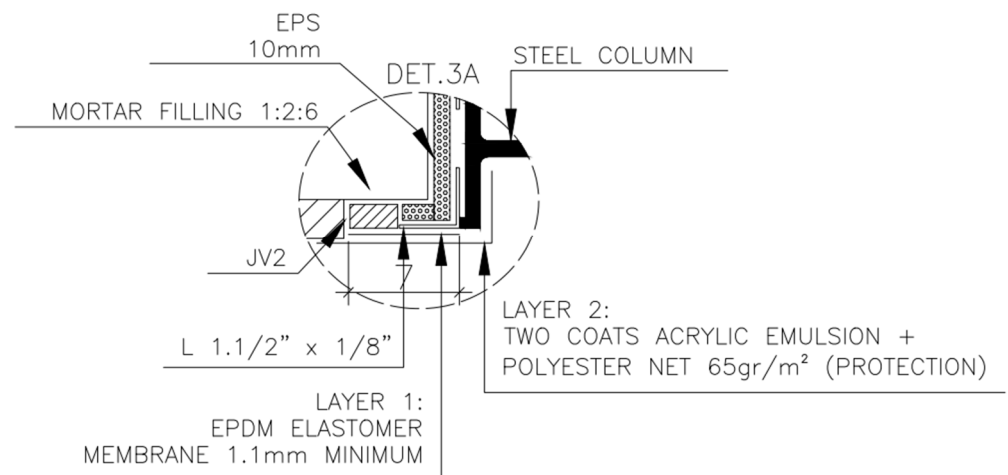


Figure 9. Detail 3A for interface INT3.

3.2. Materials

3.2.1. Walls

Ceramic blocks with dimensions of $9 \times 19 \times 29$ cm (Figure 10) were employed in the construction of the experimental model.



Figure 10. Constructing the experimental model: (a) steel frame overview; (b) masonry placement in relation to the horizontal joint; (c) masonry placement in relation to the vertical joint; (d) appearance of the model before treating the joints between the masonry and the steel beam.

On the steel frame's columns and beams, steel angles and EPS were placed such as to allow the wall to move apart from the steel frame (Figure 10b,c).

Cold-formed steel sheets were welded over the beam, simulating the edge trim in a composite steel deck slab. Concrete was then poured inside these steel sheets, simulating the placement of a slab on the steel frame's beam.

After the concrete had finished curing, two masonry courses were applied above it to conclude the structural model. The masonry wall was then coated with roughcast and plaster. The horizontal joints between the steel beam and the angles, which are not subjected to relative displacements, were stuffed with a body filler. After this process, the steel beams were painted. Figure 10d depicts the experimental model's final appearance before the joints between the masonry and the steel beam were treated.

3.2.2. Treating the Joints

Once the mortar coating had finished curing, the interfaces between the masonry and the steel beams were treated with an EPDM (ethylene–propylene–diene–monomer) elastomer membrane, a polyester net, and an acrylic emulsion. EPDM membranes possess excellent elasticity and watertightness characteristics, with a notable durability performance. Before any treatment, the region surrounding the horizontal joint was dusted and cleaned.

Non-reinforced EPDM membrane strips were used, each 7 cm wide and 1.1 mm thick. Caulking tape must be glued to the membrane so that it can fuse with the surface through a cold vulcanizing process. An adhesive was applied over the membrane strips and the caulking tape, and allowed to sit until it was dry to the touch on both parts. The caulking tape was then glued over the membrane, thus being ready for application on the joints.

The adhesive was applied in the region surrounding the joints and allowed to sit for 3 h in order to dry. Afterwards, the adhesive was applied over the outer face of the caulking tape, which was already fused with the membrane, and allowed to sit until it was dry to the touch. The tape, already fused with the membrane, was then applied over the region of the joints.

Once 20 min had elapsed from the application of the EPDM elastomer membrane over the region of the joints, a white acrylic emulsion diluted in 30% water was applied, along with a thermo-stabilized polyester net weighing 30 g/m². The first acrylic emulsion coat was applied over the EPDM elastomer membrane. The polyester net was cut wider than the caulking tape. After 6 h had elapsed from the application of the first coat of acrylic emulsion, the net was applied over the region of the joints along with a second coat of acrylic emulsion, this time undiluted. Two more acrylic emulsion coats were applied, always with an interval of 6 h between coats. Figure 11 displays a sequence of the EPDM elastomer membrane treatment applied to the experimental model.

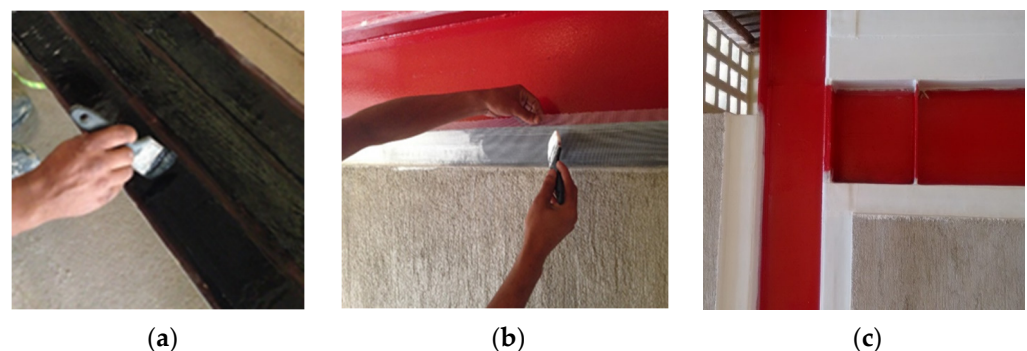


Figure 11. Treating the joints with an EPDM elastomer membrane: (a) applying adhesive over the membrane; (b) applying the polyester net with acrylic emulsion; (c) final appearance of the joints after treatment.

3.3. Methods

3.3.1. Heat Exposure and Thermal Shock Test

The experimental models were subjected to the heat exposure and thermal shock test with the aid of a radiant panel developed by Franco [31], according to what is established in ABNT NBR 15.575-4:2021 [30].

During the test, each interface of the experimental model was exposed to ten complete cycles of heat exposure and cooling. The heating was performed with a radiant panel comprised of a metallic plate and 8 electric resistances controlled through 4 thermocouples placed on the wall, connected to a system with electric contactors. The temperature of the wall's outer face was kept at 80 ± 3 °C for the duration of one hour in each cycle. Thermocouples were placed over the interfaces' joints in order to monitor temperature variations during the experiment.

After each heating cycle, the wall was cooled with water jets, the radiant panel was removed, and the wall was sprayed with water over its outer face until it reached a temperature of 20 ± 5 °C. Before cooling, thermographic images of the outer wall of the experimental model were made. At the end of each cooling phase, one cycle of the experiment was considered to be completed. Figure 12 displays the inner part of the radiant panel, and its placement over one of the interfaces tested in the experimental model.

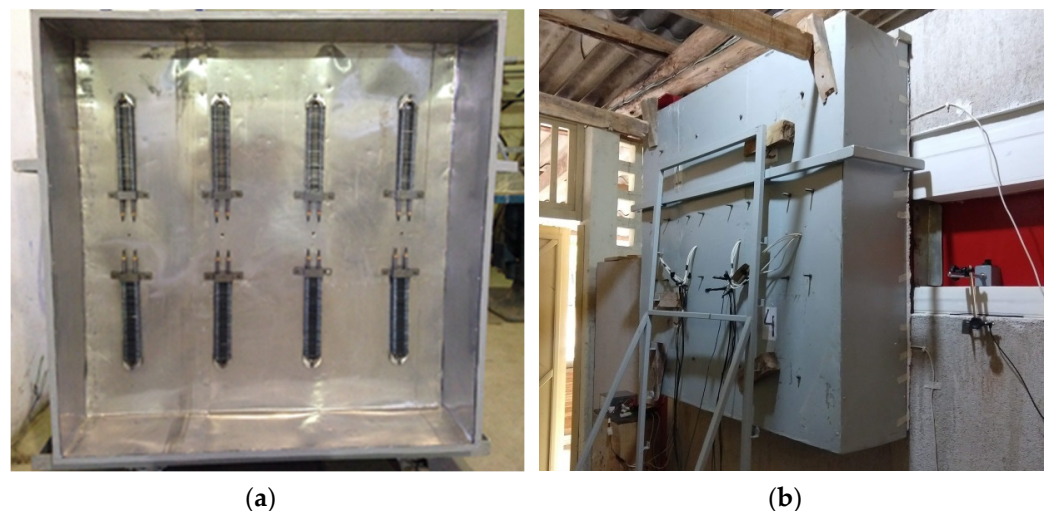


Figure 12. Radiant panel: (a) inner view of the panel; (b) positioning during the heat exposure and thermal shock experiment.

The occurrence of failures during the heat exposure and thermal shock experiment, e.g., cracks, detachments, blistering, discoloration, and other damage to the surface of the model that was subjected to experimental conditions, were registered. Therefore, although this test caused accelerated aging, the results were basically qualitative.

In order to assess the relative displacements between the masonry and the steel beam in the interfaces, displacement transducers (DT) were employed in the plane of the wall, with a 5 mm nominal displacement and ± 0.00005 mm precision. The DTs were attached to the steel beams with the aid of magnetic bases.

3.3.2. Painting of the Experimental Model

After the heat exposure and thermal shock test, the experimental model was allowed to air dry for 20 days. Since the purpose of this work was to evaluate the performance of the interfaces between masonry and steel structures that had been treated with an EPDM elastomer membrane, it was decided that the external surface of the walls should be painted.

The outer wall of the experimental model received two coats of white acrylic paint. The region where the wall interfaced with the joint treated with the EPDM elastomer membrane was not painted, in order to preserve its characteristics without alteration after the heat exposure and thermal shock test. Figure 13 displays the general appearance of the model after its external surface was painted.



Figure 13. General appearance of the wall after its external surface was painted.

The purpose of this procedure was to seal any cracks that might exist in the masonry's mortar coating, preventing potential water leaks through the surface of the wall that would interfere in the evaluation of the interfaces' watertightness performance.

3.3.3. Watertightness Test

Once the paint had finished curing, the models were subjected to the watertightness test with the aid of a watertightness chamber that could control the pneumatic pressure and water spray outflow, developed by [32] based on the recommendations in the ABNT NBR 15.575-4:2021 [30].

With the aid of an electric pump, used in association with the chamber, water was sprayed on the test region with an outflow of $3.0 \pm 0.3 \text{ L/m}^2 \text{ min}$, simulating intermittent rain. Simultaneously, with an air compressor, the test region was subjected to a pneumatic pressure of 400 Pa. Figure 14 displays a watertightness chamber placed over the interfaces tested in the experimental model.

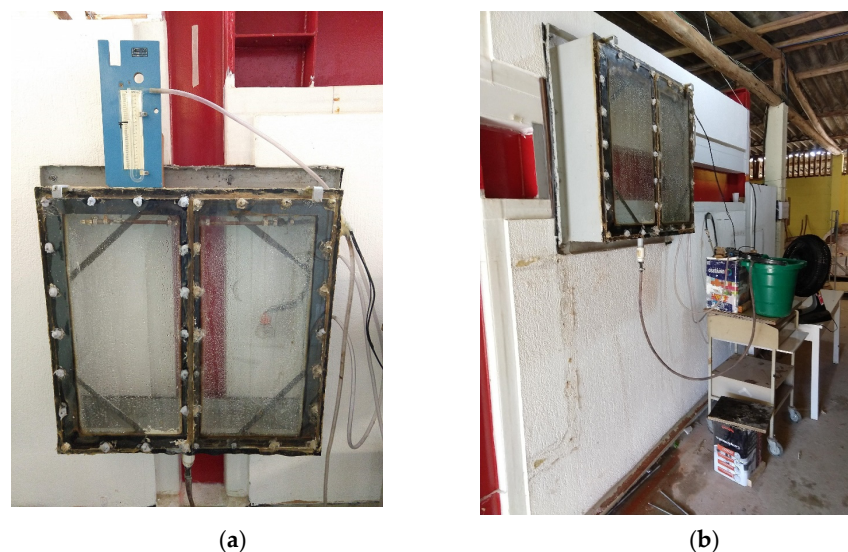


Figure 14. Watertightness chamber: (a) placement over interface INT 3; (b) placement over interface INT2.

The test was run continuously for eight hours and the inner face of the wall was photographed every 30 min. At the end of the test, the relation between the sum of the humidity stains in the opposite face of the wall and the total area of the test subject submitted to water spraying (test region) must not be higher than 10% for single-story buildings and 5% for buildings with more than one story, based on the recommendations in the ABNT NBR 15.575-4:2021 [30].

4. Results and Discussion

4.1. Heat Exposure and Thermal Shock Test Results and Evaluation

4.1.1. Interface INT1

In Figure 15, the appearance of interface INT1 of subject E2 can be observed before and after the heat exposure and thermal shock test. Small cracks can be observed in the outer test region of interface INT1 in both test subjects. In the regions of the joints that were treated with an EPDM membrane, no alterations could be detected with the naked eye.

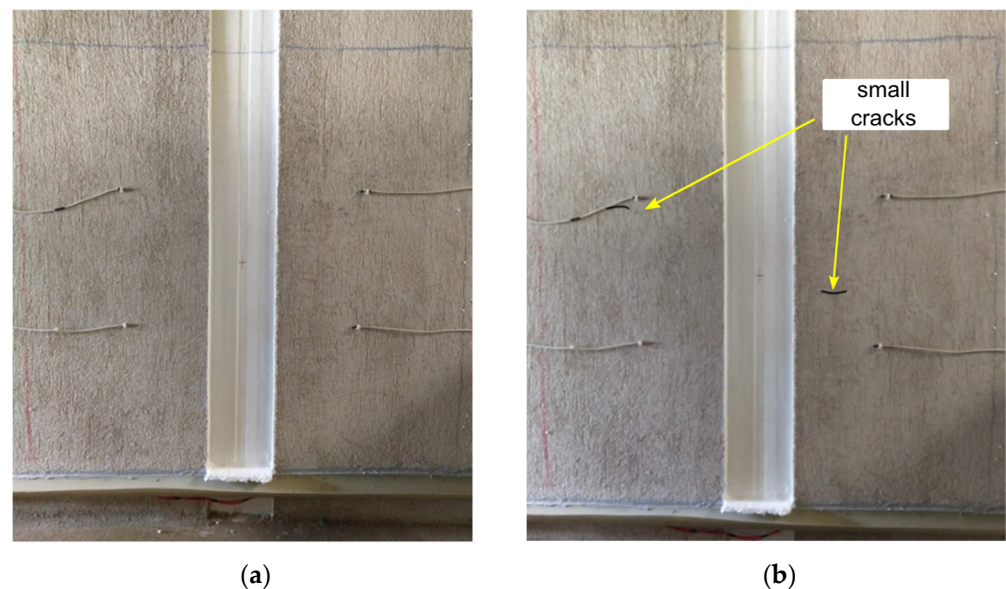


Figure 15. Appearance of interface INT1 in subject E2: (a) before the heat exposure and thermal shock test; (b) after the test.

Figure 16 displays thermographic images obtained after the end of the heating phase in the 10th cycle of the heat exposure and thermal shock test in subject E2, right after the removal of the radiant panel.

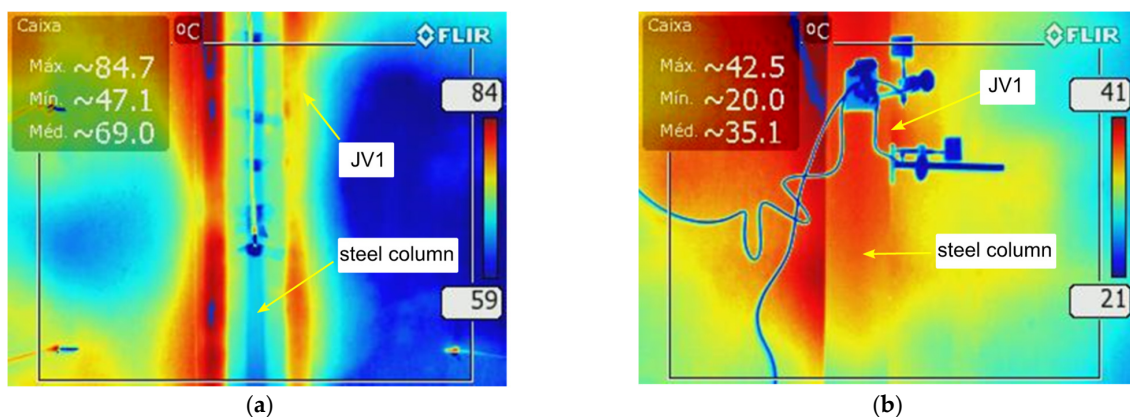


Figure 16. Temperature distribution during the heat exposure and thermal shock test in interface INT1 of subject E2 after the end of the heating phase in the 10th cycle: (a) outer face; (b) inner face.

The graph in Figure 17 displays the relative horizontal displacements between the masonry and the steel column, measured in vertical joint JV1 during some cycles in the heat exposure and thermal shock test. The maximum expansion observed in joint JV1 was 0.014 mm and the maximum contraction was 0.029 mm.

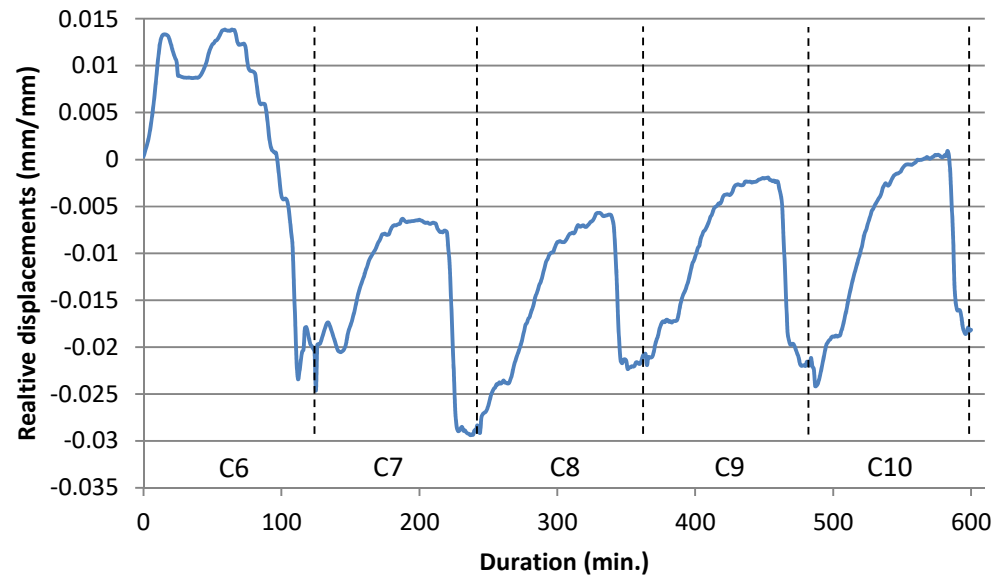


Figure 17. Relative horizontal displacements between masonry and steel column in vertical joint JV1 of interface INT1, during cycles C6 to C10.

Figure 18 displays a detail of relative horizontal displacements between the masonry and the steel column during cycle 7 of the heat exposure and thermal shock test in vertical joint JV1.

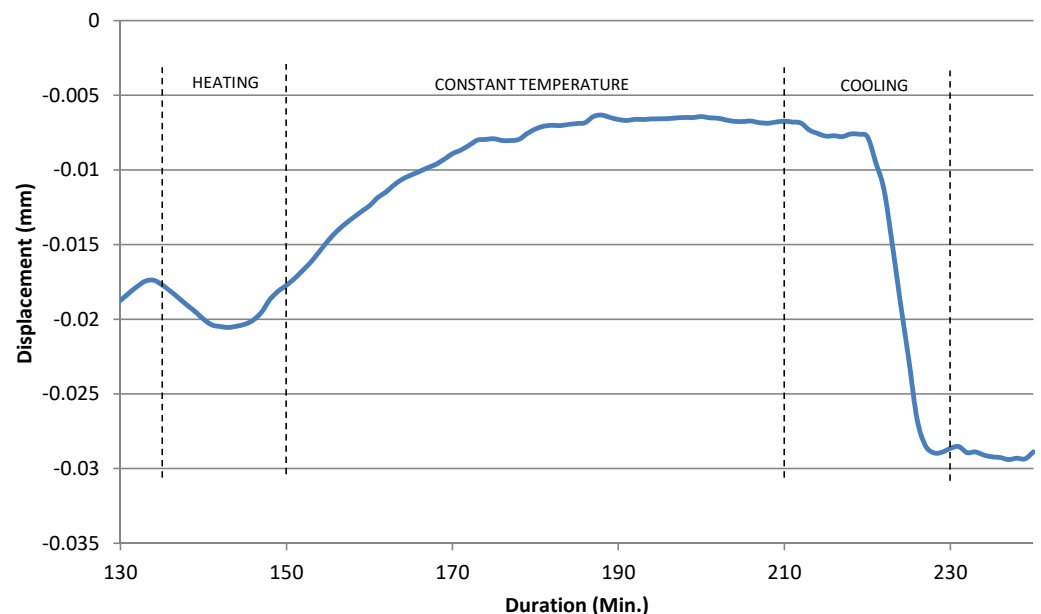


Figure 18. Relative horizontal displacements measured in the test's 7th cycle in vertical joint JV1 of interface INT1.

4.1.2. Interface INT2

In Figure 19, the appearance of interface INT2 of specimen E2 can be observed before and after the heat exposure and thermal shock test. No damage was detected in the outer

face of the region around interface INT2 in either specimen. In the region of the joints treated with the EPDM membrane, no alterations could be detected with the naked eye.



Figure 19. Appearance of interface INT2 in specimen E2: (a) before the heat exposure and thermal shock test; (b) after the test.

In the specimen's outer face, higher temperatures occurred near horizontal joints (JH1 and JH3). Figure 20 displays thermographic images obtained after the end of the heating phase in the 10th cycle of the heat exposure and thermal shock test in specimen E2, right after removing the radiant panel.

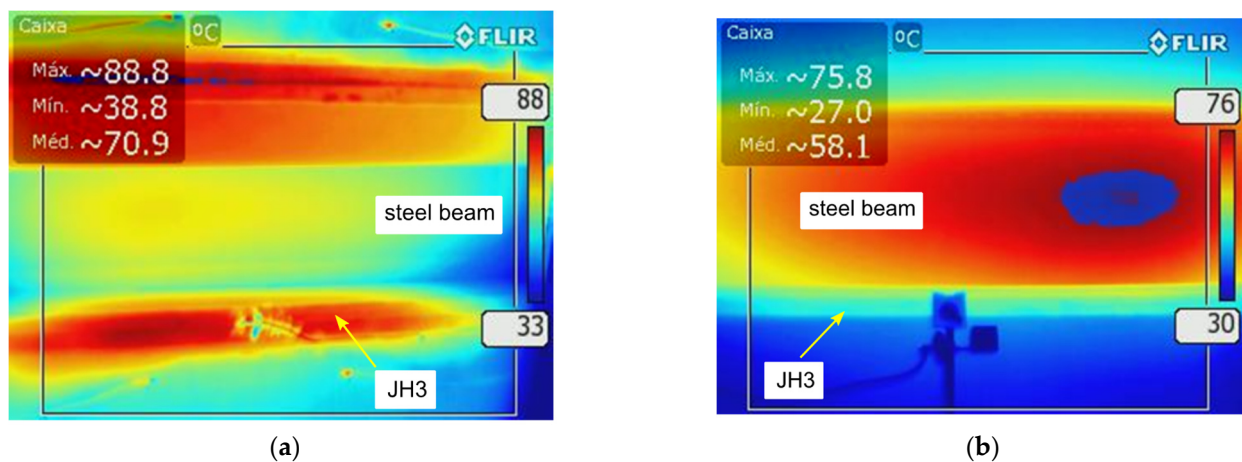


Figure 20. Temperature distribution during the heat exposure and thermal shock test of interface INT2 of specimen E2 after the end of the heating phase in the 10th cycle: (a) outer face; (b) inner face.

The graph in Figure 21 displays the relative horizontal displacements between the masonry and the steel beam measured in horizontal joint JH3 during some cycles of the heat exposure and thermal shock test. The maximum expansion observed in joint JH3 was 0.230 mm and the maximum contraction was 0.102 mm.

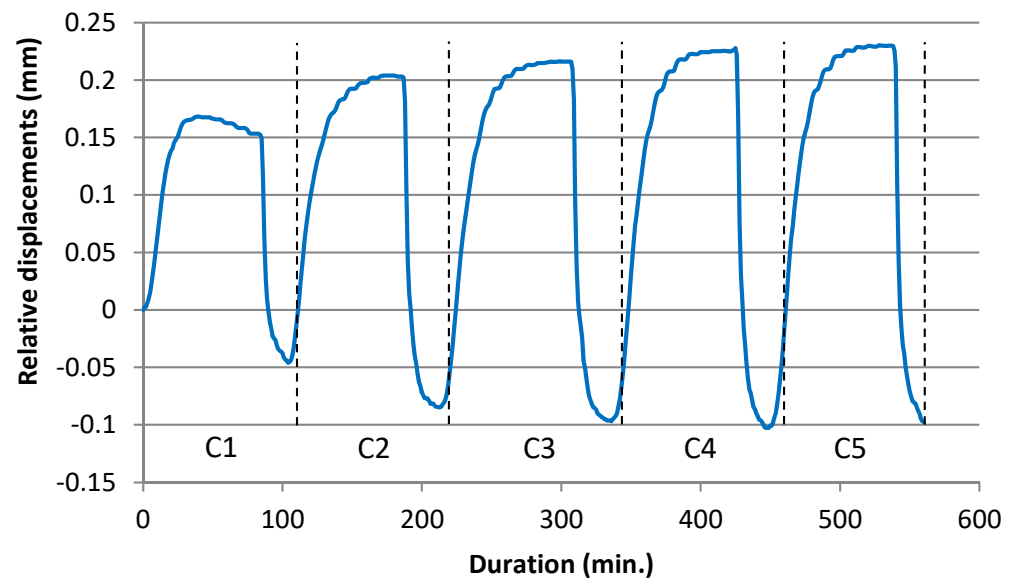


Figure 21. Relative horizontal displacements in horizontal joint JH3 of interface INT2 during cycles C1 to C5.

4.1.3. Interface INT3

After the heat exposure and thermal shock test, small cracks could be observed on the outer surface of the test region of interface INT3 in both specimens. No alterations could be perceived with the naked eye around the joints that had been treated with the EPDM elastomer membrane. Figure 22 displays the appearance of interface INT3 of specimen E2 before and after the test.

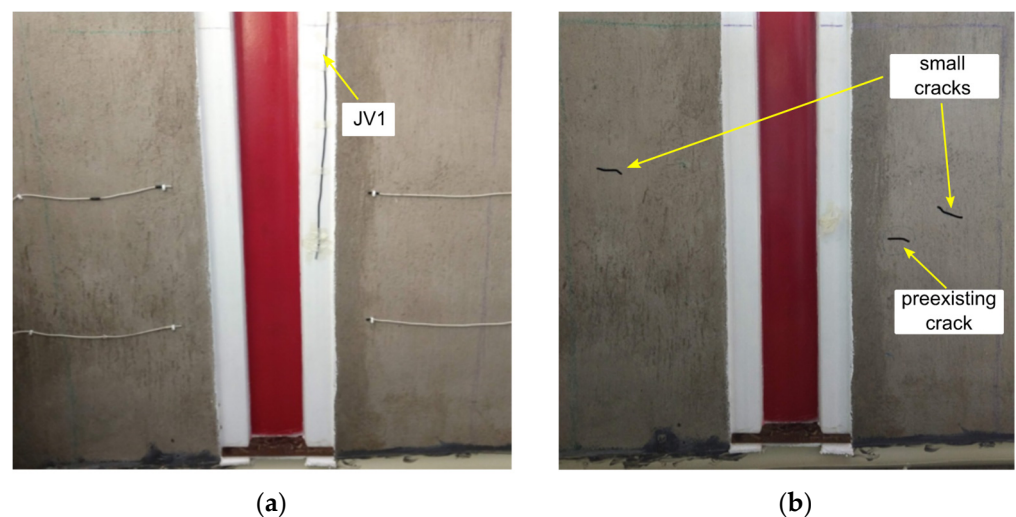


Figure 22. Appearance of interface INT3 on specimen E2: (a) before the heat exposure and thermal shock test; (b) after the test.

Figure 23 displays thermographic images obtained after the end of the heating phase in the 10th cycle of the heat exposure and thermal shock test in specimen E2, right after the removal of the radiant panel.

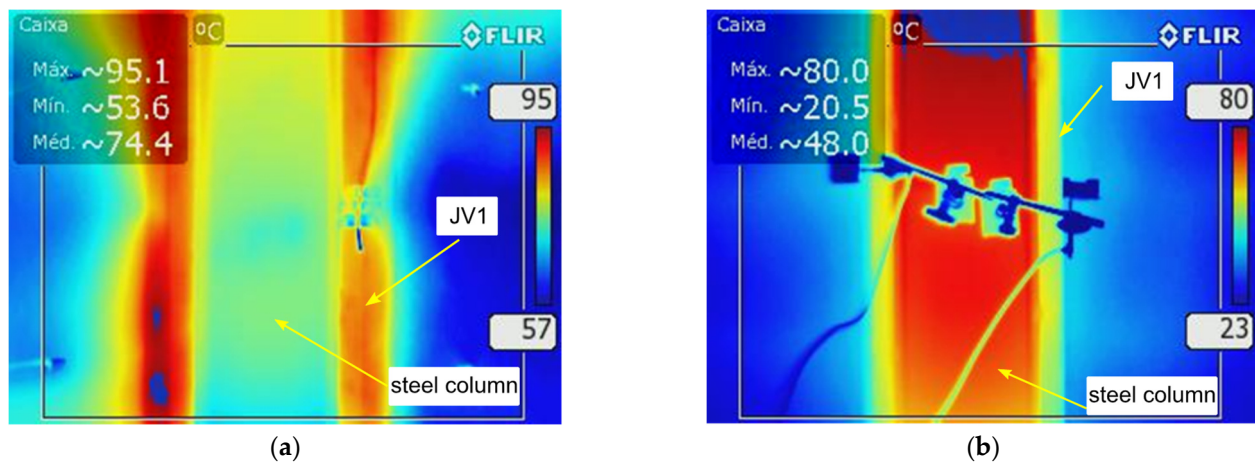


Figure 23. Temperature distribution in the heat exposure and thermal shock test of interface INT3 of specimen E2, right after the end of the 10th cycle's heating phase: (a) outer face; (b) inner face.

The graph in Figure 24 displays the relative horizontal displacements between the masonry and the steel beam measured in vertical joint JV1 during some cycles of the heat exposure and thermal shock test. The maximum expansion observed in joint JV1 was 0.024 mm and the maximum contraction was 0.743 mm.

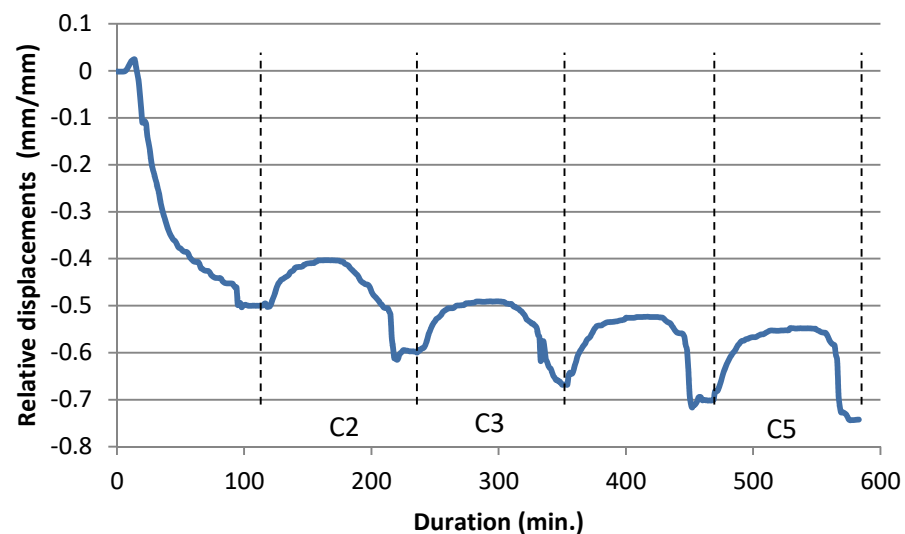


Figure 24. Relative horizontal displacements between masonry and steel beam in vertical joint JV1 of interface INT3 during cycles C1 to C5.

4.1.4. Discussion

Based on the test results (Sections 4.1.1–4.1.3), it is evident that there were no alterations visible to the naked eye after the heat exposure and thermal shock tests. Only small cracks could be observed near the locations to which the thermocouples had been fixed.

The highest temperatures observed in all tests on the wall's outer face occurred around the joints (Figures 16, 20 and 23). The outer wall temperature limit of 80 ± 3 °C was monitored and controlled. In certain moments of the heating phase, the thermocouple placed over the joints registered temperatures above 83 °C. In the thermographic images of the experimental model's outer face (Figures 16, 20 and 23), made right after the end of the heating phase, the steel beam's temperature was always lower than that of the masonry, since steel cools faster. Moreover, the lack of uniformity in temperature distribution may be attributed to the rapid variations in temperature in the model's outer face after the removal of the radiant panel. According to Figures 16, 20 and 23, the temperatures measured in the

model's inner face were significantly lower to those measured on its outer face, remaining close to room temperature.

Based on the relative displacements shown in Figures 17, 21 and 24, it can be observed that in each test cycle, the wall expanded during the heating and temperature stabilization phase, followed by a contraction. After the first test cycle, the wall accumulated a residual shrinkage. After the third cycle, the relative displacements stabilized, since the magnitude of expansion became similar to the magnitude of contraction.

According to Figure 18, the wall expanded during the heating phase and for part of the constant temperature phase. After a certain point, still in the constant temperature phase, the wall began to contract. This contradicts the initial expectation that the relative displacements would stabilize under constant temperature. This contraction can be attributed to the wall's loss of water during the constant temperature phase. A similar behavior to that observed for the tests in this paper was reported by Fontenelle [33] and Oliveira et al. [34], who measured the relative displacements between cementitious boards during a heat exposure and thermal shock test.

According to Laska [18], differential movement between masonry and steel occurs due to differences in the properties of these materials, which react differently when subjected to extreme changes in temperature. This differential or relative movement was observed in the results obtained from the heat exposure and thermal shock tests (see Figures 17, 21 and 24).

The relative displacements observed in the vertical and horizontal joints indicate that all three of the common interfaces between the masonry and the steel structure successfully allowed the relative movement of the parts, which is characteristic of the behavior of an untied interface. It was also clear that the untied interface was able to satisfactorily withstand differential movements with no damage to joints or masonry.

4.2. Watertightness Test Results and Evaluation

The results obtained in the watertightness test conducted using the three common types of interface showed that no humidity stains could be found on the inner face of any of the specimens, even after the continuous application of a pneumatic pressure of 400 Pa for eight hours. Figures 25–27 display the specimens' inner faces at the beginning and end of the watertightness test.



Figure 25. Appearance of the INT1 specimen's inner face before and after the watertightness test: (a) before; (b) after.



(a)



(b)

Figure 26. Appearance of the INT2 specimen's inner face before and after the watertightness test: (a) before; (b) after.



(a)



(b)

Figure 27. Appearance of the INT3 specimen's inner face before and after the watertightness test: (a) before; (b) after.

Moreover, no evidence of water leaks was found on the specimen's inner face after a visual evaluation of the tested areas. This result suggests that painting the specimens with acrylic paint prevented water from penetrating through possible existing cracks in the mortar coating, and that no water passed through the joints that had been treated with an EPDM elastomer membrane.

5. Conclusions

A method for treating common interface joints between masonry and steel structures—the application of an EPDM (ethylene propylene diene monomer) elastomer membrane—was proposed in this paper. The main goal of this building technique is to ensure the durability and watertightness of the interface's joints when they are subjected to aging triggered by heat exposure and thermal shock.

The identification of common interfaces between the masonry and the steel structure and the specifications of joints employed in this work were proposed after a wide investigation of solutions employed in steel structures. These interfaces were subjected to accelerated aging and assessed in regard to their watertightness performance.

The proposed interfaces between the masonry and the steel structure allowed adequate differential movements between the parts, without damaging joints and masonry. After heat exposure and thermal shock tests, only small cracks could be observed in the outer test region of all of the interfaces. In the regions of the joints treated with the EPDM membrane,

no alterations could be detected with the naked eye. The EPDM membrane remained whole, with no superficial alterations or debonding. During the cycles of the heat exposure and thermal shock test, the maximum relative horizontal displacements observed in the joints were 0.743 mm for vertical joints and 0.230 mm for horizontal joints, reproducing the expected behavior characterizing untied interfaces.

The results obtained in the watertightness test conducted using the interfaces considered here showed that no humidity stains could be found on the inner face of any of the specimens, even after the continuous application of a pneumatic pressure of 400 Pa for eight hours.

This work confirms that treating the horizontal and vertical joints in interfaces between the masonry and the steel structure with an EPDM membrane results in satisfactory durability and watertightness performances in all evaluated cases. In the long run, the joint specifications and the treatment method displayed in this work may contribute to ensuring the adequate durability performance of steel structures with in-plane discontinuous masonry walls.

Author Contributions: Conceptualization, J.L.R.P., G.d.S.V. and L.G.P.; methodology, J.L.R.P., G.d.S.V. and L.G.P.; investigation, A.d.F.B., R.N.F., M.A.d.S. and L.d.M.S.; formal analysis, A.d.F.B., J.L.R.P. and G.d.S.V.; resources, J.L.R.P. and H.V.; writing—original draft preparation, A.d.F.B.; writing—review and editing, J.L.R.P., G.d.S.V. and L.G.P.; supervision, J.L.R.P., G.d.S.V., L.G.P. and H.V.; project administration, J.L.R.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data sharing is not applicable to this article.

Acknowledgments: The authors hereby acknowledge Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brasil (CAPES)—Finance Code 001; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq); Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG); and the Federal University of Viçosa for their support in the development and publishing of this study. The authors also acknowledge the financial support of the Base Funding—UIDB/04708/2020 of CONSTRUCT—Instituto de I&D em Estruturas e Construções, funded by national funds through FCT/MCTES (PIDDAC).

Conflicts of Interest: The authors declare no conflict of interest.

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