DOI: https://doi.org/10.1016/j.jobe.2021.102235

INTERRELATIONS BETWEEN THE TYPES OF DAMAGES AND THEIR ORIGINAL CAUSES IN THE ENVELOPE OF BUILDINGS

ABSTRACT

The envelope is the skin that covers buildings and protects them from weather and outdoor actions. Consequently, this envelope is prone to have many deficiencies; the greatest percentage of deficiencies occurs in this zone. This paper analyses 2,030 cases that correspond to current Spanish buildings, from which the pathology combinations are categorised. In other words, each case studied is associated and quantified with the type of existing damage, the construction unit in which the damage occurred, and its original cause, thus showing the most recurrent and dominant combination and the construction typology where pathology combinations took place. The results could be useful for technicians to have a very significant view of the most troubled points of envelopes, so preventive measures can be adopted when writing the project and performing construction works. In this manner, damages would be reduced in the building envelope, as well as use costs would be reduced and habitability conditions would be improved, thus contributing to the most sustainable behaviour of the building process.

KEYWORDS

Deficiencies, facades, windows, roofs, typologies

1. INTRODUCTION

1.1. General framework

The building envelope is composed by the construction elements that separate the interior from the exterior and therefore is responsible for most features of building habitability conditions. In this manner, there are many related aspects when analysing the damages of the parts of an envelope (Bauer et al. 2014) (Conceição et al. 2019).

In general, damages in building is an issue discussed in research studies, but the discussion is usually focused on specific case studies and construction elements. However, the pathology parameters that influence these elements are not developed in certain research studies (Olanrewaju et al. 2010) because of the great difficulty of obtaining broad datasets related to building damages (Gaspar and de Brito 2005).

According to Andújar-Montoya et al. (2017), the main reasons of the problems in buildings are related to the design phase and the execution phase, representing most deficiencies that occur later. Other authors postulated that it is possible to remove latent deficiencies through a very thorough design (Chong and Low 2006). From this point of view, Al-Sharif et al. (2015) indicated that a building could be considered comfortable when sufficient technical features are included in a project (not just those required by the regulation, but those required by users). Other research studies have also considered the appropriate maintenance as an essential part of the operation quality (Lee et al. 2016) and absence of problems in the building (Filippín and Flores Larsen 2005).

In addition, the study of building damages is inevitably related to the repercussion on costs. Certain research studies have stated that processes to repair defective works increase the project cost by 52% (Love 2002), considering that the economic value of repairs is generally determined by both the optimization of resources and the possible deficiencies and omissions (Alba Cruz et al. 2013). To mitigate this situation and to reduce damages, some research studies have considered the obtaining of a quality management system for the design process (Alba Cruz et al. 2013) or the use of avant-garde technologies in processes (Pauwels 2014), such as the Building Information Modelling (BIM) technology (The American Institute of Architects 2013). This reduction would not be only verified in the design phase (in which this technology has already been used) but also in the phases of construction (Chou et al. 2009) and use, which are still a long way to go (Ministerio de Fomento 2015). To reduce terms and other problems from the construction deficiencies, voluntary and non-judicialized procedures could be employed (Koh et al. 2017) to solve more quickly and in a less traumatic way the possible conflicts with clients through an independent arbitrator's award (Rodríguez de la Flor 2015).

Nevertheless, the experience on the repercussion of certain types of damages and their repairs could be positive by using it as a learning (Love et al. 2018) and improvement opportunity for the future (Mills et al. 2009).

1.2. Antecedents from other research studies

As this issue is focused on the scope of the envelope and construction units in particular, such as roofs, facades and windows (Park and Song 2018), the deficiencies and rework processes are significantly related to humidity (Pereira et al. 2018), rainfalls (Olsson 2018), the entry of water through various junctions and troubled points (Boudreaux et al. 2018) or the disposition of waterproofing (Walter et al. 2005). Claddings have also a key role in envelopes (Sá et al. 2015) and are involved in their pathology processes (Garcez et al. 2012). Azhar (2011) determined that the existing deficiencies in the claddings of various buildings increase if quality control is not rigorously monitored. For this reason, an analysis process and a previous control of the technical construction specifications of the requirements of facades (Carretero-Ayuso et al. 2018) and roofs (Carretero-Ayuso et al. 2016) could significantly reduce the number of possible damages in the use phase.

Historically, roofs are among the construction elements most prone to have problems (Conceição et al. 2017), according to old construction treaties (Ger Lobez 1898). All the possible deficiencies in roofs are not pathological, but some can be catastrophic (Piskoty et al. 2013). Scientific references on roofs are usually focused on both the analysis of constituent materials and their application (Misar and Novotný 2017) and the study of certain typologies (Liu et al. 2019), such as green roofs (Feitosa and Wilkinson 2020). They are also focused on the mechanical behaviour of the junctions between waterproofing pieces (Gonçalves et al. 2008), the action of the suctions generated by wind (Silva et al. 2010), the junctions subjected to artificial weather (Gonçalves et al. 2011) or the way of placing the bindings between sheets (Ko et al. 2006)

Regarding facades, some research studies are also focused on materials, and the conception and design errors are responsible for 60% of damages in facades (Silvestre and de Brito 2011). A reason is the difficulty of providing a general typology of facade (Molnár and Ivanov 2016) that includes an ideal solution from a construction point of view (Hradil et al. 2014). Other reasons are the many elements that constitute facades (Carraro and Oliveira 2015) and the variability of the construction systems available (Gaspar, K. et al. 2016).

On the other hand, when diagnosing an existing damage, its original causes are usually repeated in the current working process of other buildings, so these cases should be disseminated to improve the building sector (Meiss and Muñoz 2015). This situation also takes place in other countries, where facades and roofs generate most building problems (Ilozor et al. 2004), as in Spain. For this reason, knowing the recurrence percentages of the most common deficiencies is determinant to know the weaknesses and is a first step to obtain minimum quality results in future buildings (Lee et al. 2016).

1.3. Goals of this study

In this sense, the statistical development of complaints and the analysis of deficiencies could be useful to study in detail what is today happening in the building sector and to know what type of deficiencies are the most common in a given country (Sarman et al. 2015). This paper aims to responding these issues related to the envelope of current buildings built in Spain.

For this purpose, more than two thousand cases have been used in this study. This number is greater than those taken as a basis in most engineering research studies, according to the analysis of the scientific literature from the last two decades. Moreover, there are no research studies based on a source of data and a methodology with the same characteristics as those developed in this paper. In addition, the amount of data used corresponds to Spain as a whole and covers all the cases to be analysed.

In other studies, most occasions belong to the same construction or property development company, with a reduced number of cases, or belong to surveys based on them. In this paper there is no parameter that links cases, thus guaranteeing the independence of the results obtained.

2. METHODOLOGY

The methodology consisted of acquiring data from the expert's reports on liability insurances of technical architects and building engineers in Spain (MUSAAT 2015). The reports selected were those which initiated dossiers of a case based on the owners' complaint related to the existence of constructive damages in their buildings. These data were acquired from the dossiers meeting the condition of having a definitive court's decision, belonging to the dossiers initiated between 2013 and 2015 (SERJUTECA 2015). It took several years to make these complaints, to file a lawsuit, to have a judgement, to turn these judge's decisions into high judicial instances, and eventually to give a definitive and unappealable judgement. At this point was when records were part of the research: they were read, analysed, classified, and assessed.

A total of 2,030 cases have been considered in this study. All belong to the outdoor building envelope: 1,229 cases belong to the vertical side of such envelope, and the remaining cases (801) belong to the horizontal side. In addition, many parameters have been included, thus enriching the study but making it more complex:

-Base parameters: Composed by joining three ‘descriptors’, which are described above. These parameters are required to identify a case: location/damage/original cause. There are 58 different concepts in them (Table 1).

-Complementary parameters: Composed by other aspects that characterize the dataset studied, either additionally (building typology= 4 building formats) or based on the interrelation among the ‘descriptors’ mentioned (different pathology combinations= 228 types).

DESCRIPTOR	CODE	CONCEPT
Descriptor 1: Construction units	**Code U**	**Name of the construction unit**
	U1	Window frameworks
	U2	Pitched roofs
	U3	Flat roofs
	U4	Uncoated facades
	U5	Coated facades
Descriptor 2: Types of damages	**Code D**	**Name of the damage**
	D1	Biological attack
	D2	Spalling and chipped parts
	D3	Thermal anomalies
	D4	Efflorescence
	D5	Wind entry
	D6	Direct infiltrations of water and/or dripping
	D7	Cracks in the central part of wall sections
	D8	Cracks in the finish claddings
	D9	Cracks in the perimeter parapets of the roof
	D10	Cracks in the lateral side walls of the roof (gables)
	D11	Horizontal cracks in slab fronts
	D12	Vertical cracks in pillar alignments
	D13	Detachments in corners (junctions between walls sections)
	D14	Detachments in structural patching
	D15	Condensation humidity
	D16	Capillary humidity
	D17	Infiltration humidity
	D18	Absence of planimetry
	D19	Breakage of pieces or elements
	D20	Others/no data
Descriptor 3: Types of original causes of damages	**Code C**	**Name of the original cause**
	C1	Continuous presence of humidity
	C2	Absence or deficiency of adherence to the support
	C3	Absence or deficiency of anti-drip groove, gutter or drainpipes
	C4	Absence or deficiency of sealing
	C5	Absence or deficiency execution of singular elements
	C6	Absence of waterproofing
	C7	Absence of barrier against capillary humidity
	C8	Deficient disposition of waterproofing sheet
	C9	Deficient disposition of tiles

	C10	Absence or inappropriate ventilation of the air gap of the roof
	C11	Incorrect disposition of the thermal insulator
	C12	Absence or deficiency of construction junctions
	C13	Absence or deficiency of patching in structural elements
	C14	Inappropriate or badly placed lintels
	C15	Direct contact with the ground
	C16	Defect or absence of verticality
	C17	Defects in the fixing of windows
	C18	Deficient support base of brick wall sections
	C19	Deficient quality of cement claddings
	C20	Deficient treatment of wood
	C21	Deficient junction with roof bowls and drains
	C22	Bad junction with the salient elements of the facade
	C23	Existence of thermal bridges
	C24	Absence or deficient junction with vertical surfaces
	C25	Absence of individual junctions between pieces (butt-joint installation)
	C26	Inappropriate or deficient material
	C27	Presence of dilatation movements not considered
	C28	Inappropriate slope of the roof element
	C29	Presence of phreatic level not considered
	C30	Absence of protection of the punching of the waterproofing sheet
	C31	Inappropriate anchorage or fastening system
	C32	Insufficient assembly between brick walls or interrupted built joints
	C33	Unknown cause or without diagnosis

Table 1 – Codification and relation of the descriptors used in the research

The analysed reports correspond to 100% of those in Spain in the period mentioned. That circumstance, along with the complexity to obtain this type of data, implies that this research has no precedents because of both the number of cases analysed and the origin of the source of data.

As previously mentioned, each case to be studied is characterized by 3 descriptors:

- Descriptor 1 (construction unit). This element is where the problem or deficiency is. This descriptor are described in the upper section of Table 1. They are 5 construction units that belongs to the building envelope.
- Descriptor 2 (type of damage). It is the problem or deficiency itself. The 20 types indicated in the central section of Table 1 have been characterized according to the determination of the experts who made the reports of each case.
- Descriptor 3 (type of original cause). It is the reason why a problem or deficiency arises. The 33 types indicated in the lower section of Table 1 have been typified also according to the experts who visited the buildings of each case.

Apart from these 3 descriptors, another aspect has also been considered to provide the cases with greater concision and characterization: the building typology. According to this criterion, each case is assigned to a ‘building block’, an ‘isolated single-family’, a ‘semi-detached single-family’, and a ‘non-residential buildings’.

3. RESULTS

3.1. Individual results per descriptor

The presence percentage of each pathology descriptor was determined.

Descriptor 1 analysed the existing construction units. According to Figure 1, the coated facades was where the number of cases was greater (U5=29.75%), followed by flat roofs (U3=27.09%) and window frameworks (U1=16.80%).

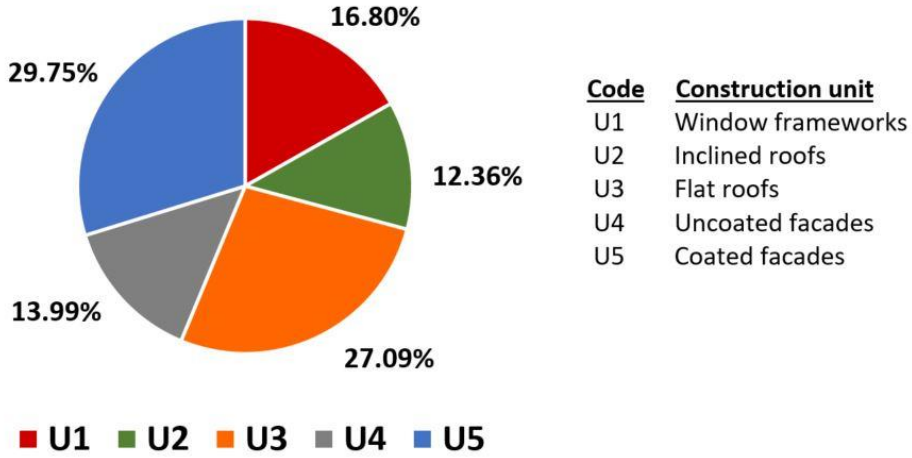

Fig. 1 – Percentage of cases obtained per construction unit

To show the results of the descriptor 2 indicated in Table 1 (type of damage), the diagram of accumulated percentages was drawn and included in Figure 2. The most present type of damage was 'infiltration humidity', which occurred in more than one-third of the total (D17=33.35%), then 'direct infiltrations of water and/or dripping' (D6=17.54%), and finally 'condensation humidity' (D15=15.62%). From these three types of damages (called 'primary'), the percentages hugely decreased because only their sum covered the two-thirds of the total of cases (66.51% of the total), thus obtaining a Pareto relationship ~16-67.

There was an internal asymmetry in the percentage obtained by these three first damages as the second and third position summed the equivalent of that obtained by the first position. For this reason, the subset D6 and D15 (=33.16%) was called 'basic primary [BP], and the first damage (D17=33.35%) was called 'critical primary [CP] because of the high individual concentration of cases (Figure 2).

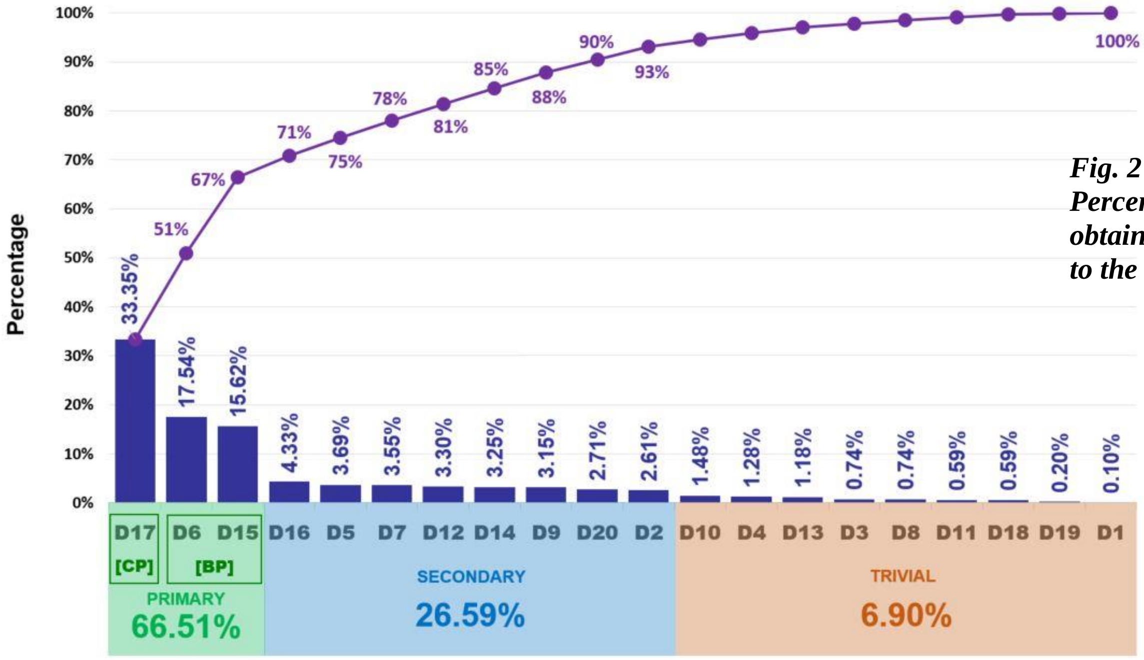

Fig. 2 – Percentages of cases obtained according to the type of damage

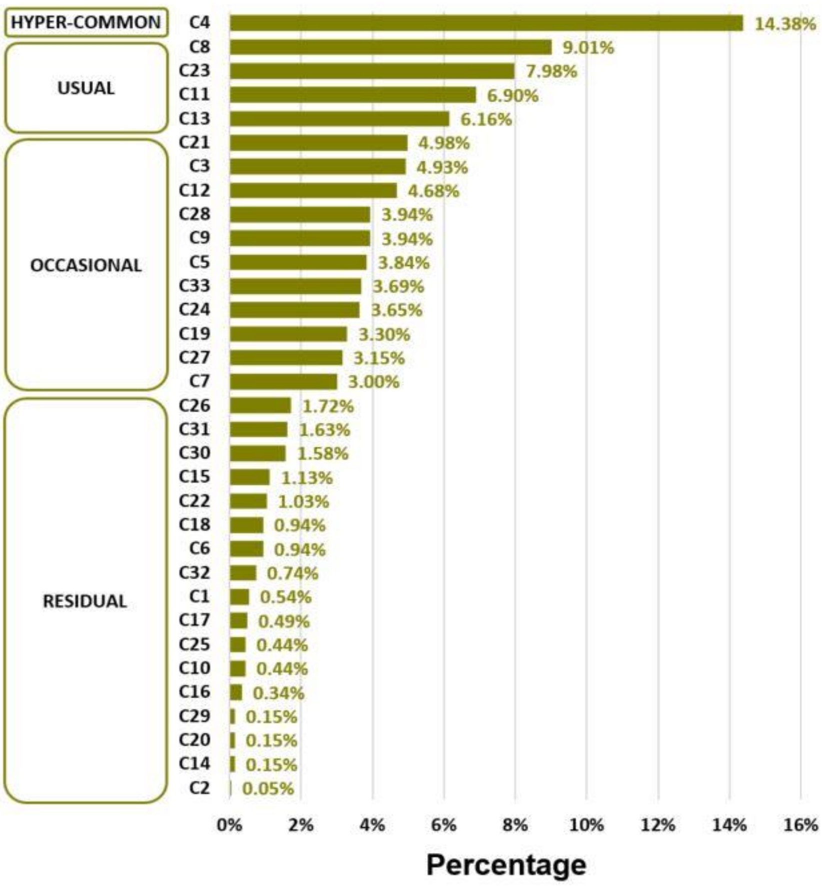

Fig. 3 – Percentages of cases obtained according to each original cause

On the other hand, there were a series of damages with an intermediate presence ('secondary' damages: D16+D5+D7+D12+D14+D9+D20+D2) which were between 2% and 15% and all together summed 26.59% of the total. Finally, there were 9 types of damages with marginal presence ('trivial damages'), whose individual presence percentage was lower than 2% (see the terminology section at the end of this paper).

Figure 3 is included to show the values obtained in the descriptor 3 defined in Table 1 (types of original causes); this figure shows a decreasing order of the presence percentages of this descriptor. The most prevalent original causes were 'absence or deficiency of sealing' (C4=14.38%) and 'deficient disposition of waterproofing sheet' (C8=9.01%), which have a construction relationship with the types of damages showed in Figure 2.

According to the presence of each original cause, four collections were created (sets according to the percentage similarity), as Figure 3 shows (read also the definitions included at the end of this paper, in the terminology section). In this manner, C4 was called 'hyper-common', and C8+C23+C11+C13 were called 'usual'.

3.2. Results per construction unit and type of damage

Figure 4 shows the relationship between the type of damage (descriptor 2 from Table 1) and the construction unit in which they occurred (descriptor 1 from Table 1) to precisely know which damages are involved in each place and to have detailed information to be used later in the prevention during the project stage.

Following a combined nomenclature based on Table 1, the damages with a greater percentage in comparison with the total of the set were $D6_{U3}$=12.41%, $D17_{U3}$=9.75%, $D17_{U1}$=8.42%, $D17_{U5}$=8.33%, and $D15_{U1}$=6.06%. Thus, the 'infiltration humidity' (D17) was on the top in 3 out of these 6 times.

Furthermore, the types of damage D6, D15, D17, and D20 were present in the two types of roof (U2 and U3). As for the two variants of facades (U4 and U5), the same types of damage were repeated, except D19 (breakage of pieces or elements) which only occurred in the uncoated facades. Finally, the types of damage which were common in the 5 construction units were 'condensation humidity' (D15) and 'infiltration humidity' (D17), and again the key role of humidity in the set was notable.

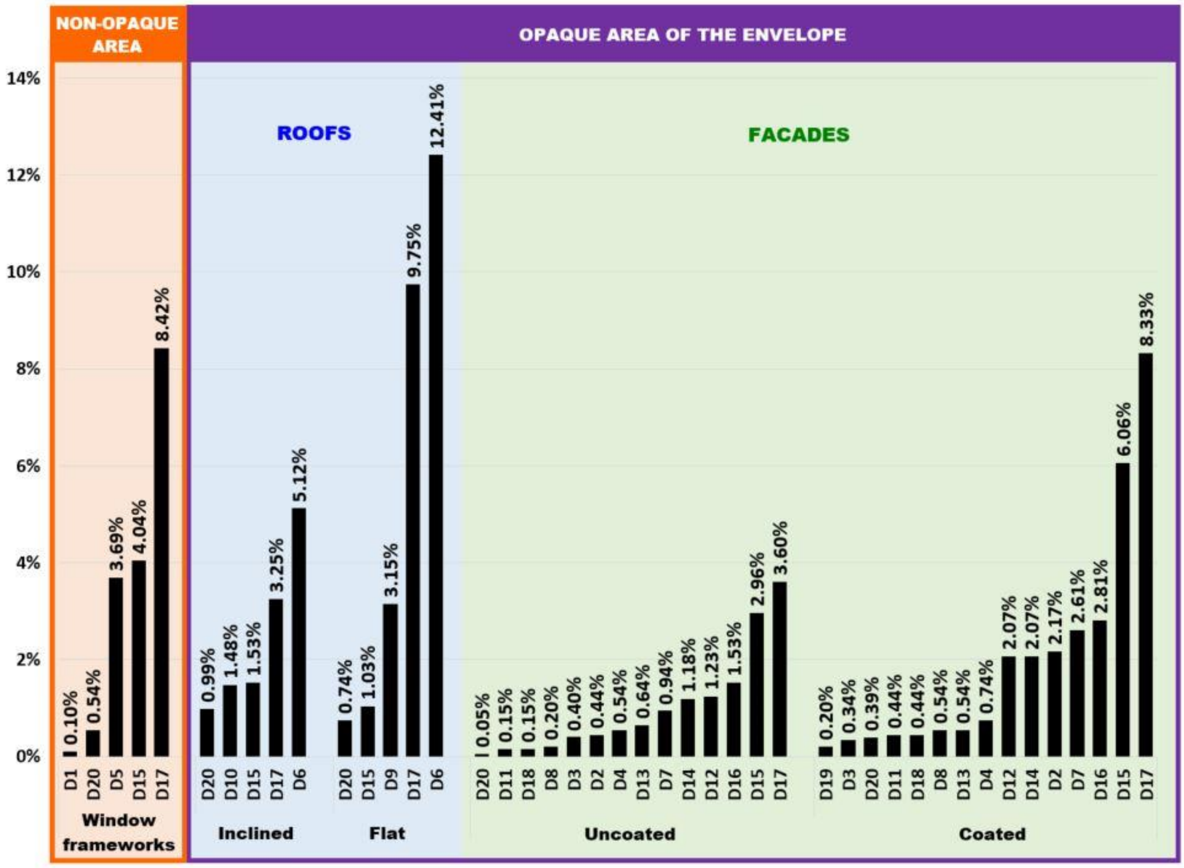

Fig. 4 – Distribution of the damages in each construction unit

3.3. Results per pathology combinations

A pathological combination is the construction interrelation among the 3 descriptors (construction unit/damage/original cause); that is, the confirmation of the types of damages within a construction element, which is their specific original cause, and finally the quantification of the number of times those cases occur.

This study verified 228 types of pathology combinations (developed in Table 2 and Table 3). Among them, 70 were in roofs (U2+U3) –the horizontal side of the envelope– and 158 were in facades and window frameworks (U1+U4+U5) –the vertical side of the envelope–.

The pathology combinations for the construction units of the horizontal envelope (see Table 2) were as follows: in the pitched roofs (U2), there were 5 ‘groups of pathology combinations’ *(those sharing the same damage in a construction unit given: number of cells of the ‘damage column’ in that table)* and 36 different types of pathology combinations. The most numerous group was that due to ‘direct infiltrations of water and/or dripping’ (D6=104 cases), followed by the group of ‘infiltration humidity’ (D17=66 cases) and ‘condensation humidity’ (D15=31 cases). As for flat roofs (U3), there were 5 ‘groups of pathology combinations’ and 34 different types of pathology combinations. In this construction unit, the most numerous group was that due to ‘direct infiltrations of water and/or dripping’ (D6=252 cases), followed by the group of ‘infiltration humidity’ (D17=198 cases) and ‘condensation humidity’ (D9=64 cases).

INTERRELATION CONSTRUCTION UNIT / DAMAGE / ORIGINAL CAUSE IN ROOFS

Pitched roofs - U2

Damage	Cause	Number	Subtotal
D6	C4	1	104
	C5	28	
	C8	5	
	C9	45	
	C21	5	
	C24	12	
	C27	1	
	C28	6	
	C33	1	
D10	C5	6	30
	C10	5	
	C12	3	
	C24	1	
	C27	15	
D15	C5	1	31
	C8	2	
	C9	3	
	C10	4	
	C11	19	
	C27	1	
	C33	1	
D17	C4	3	66
	C5	12	
	C8	2	
	C9	25	
	C11	1	
	C12	1	
	C24	3	
	C27	2	
	C28	16	
	C33	1	
D20	C5	7	20
	C9	7	
	C11	2	
	C27	1	
	C28	3	

Flat roofs - U3

Damage	Cause	Number	Subtotal
D6	C4	14	252
	C5	8	
	C8	93	
	C12	2	
	C21	71	
	C24	38	
	C27	4	
	C28	6	
	C30	16	
D9	C4	1	64
	C5	2	
	C12	22	
	C21	1	
	C24	1	
	C27	37	
D15	C4	1	21
	C8	3	
	C11	16	
	C24	1	
D17	C4	6	198
	C5	12	
	C8	78	
	C12	1	
	C21	21	
	C24	18	
	C27	2	
	C28	44	
	C30	16	
D20	C4	2	15
	C5	2	
	C12	2	
	C21	3	
	C27	1	
	C28	5	

DATA QUANTIFICATION IN U2
Number of groups of pathology combinations in U2: 5
No of pathology combinations in U2: 36
Number of cases in this construction unit: 251

DATA QUANTIFICATION IN U3
Number of groups of pathology combinations in U3: 5
No of pathology combinations in U3: 34
Number of cases in this construction unit: 550

Table 2 – Relation and quantification of the pathology combinations in the horizontal side of the envelope

INTERRELATION CONSTRUCTION UNIT / DAMAGE / ORIGINAL CAUSE IN FACADES AND WINDOW FRAMEWORKS

Window frameworks - U1

Damage	Cause	Number	Subtotal
D1	C20	1	2
	C33	1	
D5	C4	49	75
	C20	1	
	C26	7	
	C33	18	
D15	C4	6	82
	C23	69	

Uncoated facades - U4

Damage	Cause	Number	Subtotal
D2	C1	1	9
	C3	1	
	C12	3	
	C26	2	
	C31	2	
D3	C11	7	8
	C31	1	
D4	C1	2	11

Coated facades - U5

Damage	Cause	Number	Subtotal
D2	C1	1	44
	C4	3	
	C18	1	
	C19	6	
	C25	3	
	C26	7	
	C31	23	
D3	C11	7	7

	C26	2	
	C33	5	
D17	C4	146	171
	C20	1	
	C26	2	
	C33	22	
D20	C4	2	11
	C26	1	
	C33	8	

DATA QUANTIFICATION IN U1
Number of groups of pathology combinations in U1: 5
Number of pathology combinations in U1: 17
Number of cases in this construction unit: 341

	C3	4	
	C19	1	
	C26	3	
	C33	1	
D7	C12	7	19
	C13	1	
	C18	3	
	C19	3	
	C25	1	
	C26	3	
	C32	1	
D8	C18	2	4
	C32	1	
	C33	1	
D11	C18	1	3
	C32	2	
D12	C4	2	25
	C12	12	
	C13	4	
	C18	3	
	C32	4	
D13	C12	3	13
	C13	8	
	C32	1	
	C33	1	
D14	C1	1	24
	C12	4	
	C13	18	
	C33	1	
D15	C11	37	60
	C23	21	
	C26	1	
	C33	1	
D16	C7	23	31
	C15	6	
	C29	2	
D17	C1	2	73
	C3	26	
	C4	11	
	C6	5	
	C13	16	
	C15	1	
	C19	1	
	C22	7	
	C33	4	
D18	C16	3	3
D20	C3	1	1

DATA QUANTIFICATION IN U4
Number of groups of pathology combinations in U4: 14
Number of pathology combinations in U4: 55
Number of cases in this construction unit: 284

D4	C3	8	15
	C19	5	
	C26	1	
	C33	1	
D7	C1	1	53
	C2	1	
	C4	2	
	C12	6	
	C13	1	
	C18	3	
	C19	35	
	C25	1	
	C26	1	
	C31	1	
	C32	1	
D8	C14	2	11
	C17	8	
	C18	1	
D11	C12	4	9
	C13	2	
	C14	1	
	C18	1	
	C25	1	
D12	C4	5	42
	C12	18	
	C13	3	
	C17	1	
	C19	5	
	C22	2	
	C26	1	
	C32	5	
	C33	2	
D13	C12	1	11
	C13	6	
	C18	1	
	C25	1	
	C26	1	
	C33	1	
D14	C12	4	42
	C13	31	
	C18	2	
	C19	3	
	C31	1	
	C33	1	
D15	C1	1	123
	C11	49	
	C19	2	
	C23	71	
D16	C4	1	57
	C7	38	
	C15	16	
	C29	1	
	C33	1	
D17	C1	2	169
	C3	59	
	C4	37	
	C6	14	
	C13	35	
	C17	1	
	C19	2	
	C22	12	
	C25	1	
	C26	1	
	C31	3	
	C33	2	
D18	C16	4	9
	C18	1	
	C19	3	
	C26	1	

D19	C25	1	4
	C26	1	
	C31	2	
D20	C3	1	8
	C11	2	
	C12	2	
	C19	1	
	C23	1	
	C33	1	

DATA QUANTIFICATION IN U5
Number of groups of pathology combinations in U5: 15
Number of pathology combinations in U5: 86
Number of cases in this construction unit: 604

Table 3 – Relation and quantification of the pathology combinations in the vertical side of the envelope

The pathology combinations for the construction units of the vertical envelope (see Table 3) were as follows: in window frameworks (U1), there were 5 ‘groups of pathology combinations’ and 17 different types of pathology combinations. The most numerous group was that due to ‘infiltration humidity’ (D17=171 cases), followed by the group of ‘condensation humidity’ (82 cases) and the group of ‘wind entry’ (D5=75 cases). As for uncoated facades (U4), there were 14 ‘groups of pathology combinations’ and 55 types of pathology combinations. In this construction unit, the most numerous group was that due to ‘infiltration humidity’ (D17=73 cases), followed by the group of ‘condensation humidity’ (D15=60 cases) and the group of ‘capillary humidity’ (D16=31 cases). Finally, as for coated facades (U5), there were 15 ‘groups of pathology combinations’ and 86 different types of pathology combinations. In this construction unit, the most numerous group was that due to ‘infiltration humidity’ (D17=169 cases), followed by the group of ‘condensation humidity’ (D15=123 cases) and the group of ‘capillary humidity’ (D16=57 cases).

To be seen more easily, 3 different pathology combinations were chosen from the 44 groups of pathology combinations described in the two previous tables. These 3 pathology combinations had a larger number of cases by each construction unit (and therefore, the most important pathology combinations: 15 in total). These 15 pathology combinations were called ‘recurrent’ (see Table 4 and the terminology section at the end of the paper), and each was designated with a letter from A to O, as Figure 5 shows.

The recurrent combinations that obtained a larger number of cases as a whole (and called ‘frequent’ –marked with # in the table–) were as follows: ‘A’ *(‘Window frameworks’ - ‘Infiltration humidity’ - ‘Absence or deficiency of sealing’;146 cases; 7.19%* –see Figure 6–*)* and ‘G’ *(‘Flat roofs’*

- *‘Direct infiltrations of water and/or dripping’ - ‘Deficient disposition of waterproofing sheet’; 93 cases; 4.58%).*

CONSTRUCTION UNIT		DAMAGE	ORIGINAL CAUSE	CASES	REF
Window frameworks	U1	D17	C4*	146 #	A*
	U1	D15	C23	69	B
	U1	D17	C4	49	C
Pitched roofs	U2	D6	C9*	45	D*
	U2	D6	C5	28	E
	U2	D17	C9	25	F
Flat roofs	U3	D6	C8*	93 #	G*
	U3	D17	C8	78	H
	U3	D6	C21	71	I
Uncoated facades	U4	D15	C11*	37	J*
	U4	D17	C3	26	K
	U4	D16	C7	23	L
Coated facades	U5	D15	C23*	71	M*
	U5	D17	C3	59	N
	U5	D15	C11	49	O
In the right column (‘Ref’ –reference–), the dominant pathology combinations in each construction unit is marked with an asterisk (*). In the column of cases, the most frequent pathology combinations of the total of the set studied in the research are marked with a hash (#).					

Table 4 – The most recurrent pathology combinations per construction unit. A graphic is included in the middle that represents these pathology combinations in comparison with the total of cases.

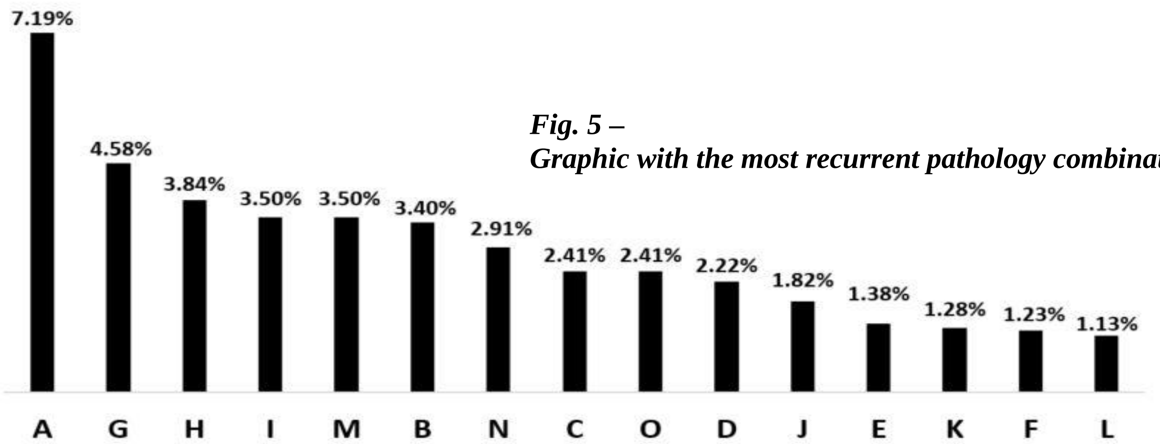

Fig. 5 –
Graphic with the most recurrent pathology combinations

A photographic example of the pathology combination A, which obtained the larger number of cases in this research on deficiencies in the external envelope (146 times). It is the damage due to infiltration humidity (D17), located in the construction unit of window frameworks (U1) and caused by the absence or deficiency of sealing (C4).

Photograph: Manuel J. Carretero-Ayuso

Fig. 6 – Photography of a case that belongs to the pathology combination A

The following appraisals can be made from this table: damage D17 occurred 6 times, and damages D6 and D15 occurred 4 times. On the other hand, the original causes C3, C4, C8, C9, C11, and C23 occurred 2 times.

The most important interrelation U/D/C by each construction unit should be known, so they could be treated (either in project or in work) to reduce the number of deficiencies in future buildings. These interrelations were called 'dominant pathology combinations' (see the terminology section at the end of the paper) and are marked with * in Table 4. They corresponded to:

- -Pathology combination A: There were 146 cases. They corresponded to '*window frameworks where there are damages of infiltration humidity caused by the absence or deficiency of sealing'* (U1/D17/C4).
- -Pathology combination D: There were 45 cases. They corresponded to *'pitched roofs in which there are damages of direct infiltrations of water and/or dripping caused by the deficient disposition of tiles'* (U2/D6/C9).
- -Pathology combination G: There were 93 cases. They corresponded to *'flat roofs in which there are damages of direct infiltrations of water and/or dripping caused by the deficient disposition of waterproofing sheet'* (U3/D6/C8).
- -Pathology combination J: There were 37 cases. They corresponded to '*uncoated facades where there are damages of condensation humidity caused by an incorrect disposition of the thermal insulator'* (U4/D15/C11).
- -Pathology combination M: There were 71 cases. They corresponded to '*coated facades where there are damages of condensation humidity caused by the existence of thermal bridges'* (U5/D15/C23).

3.4. Results per building typology

A comparative study of the percentages of each type of damage according to the building typologies (building block, isolated single-family, semi-detached single-family, and non-residential buildings) was conducted; this breakdown can be useful to understand where each building typology is more widespread. According to the values obtained in Table 5, the largest number of cases were in the building block as more than the half of the situations of the set studied occurred there (54.93%), and the most concentration damages were in D17 (18.62%) and D6 *(*10.10%). Based on the results obtained in the other typologies, humidity and infiltration were the most prevalent damages, regardless of the building typology considered.

Code of the type of damage	Percentage of cases [%]				
	Block building	Isolated single-family	Semi-detached single-family	Non-residential buildings	Total
D1	0.10 *(100)*	0 *(0)*	0 *(0)*	0 *(0)*	0.10 *(100)*
D2	1.58 *(60.38)*	0.54 *(20.75)*	0.44 *(16.98)*	0.05 *(1.89)*	2.61 *(100)*
D3	0.25 *(33.33)*	0.44 *(60.00)*	0.05 *(6.67)*	0 *(0)*	0.74 *(100)*
D4	0.64 *(50.00)*	0.34 *(26.92)*	0.25 *(19.23)*	0.05 *(3.85)*	1.28 *(100)*
D5	2.17 *(58.67)*	0.59 *(16.00)*	0.89 *(24.00)*	0.05 *(1.33)*	3.70 *(100)*
D6	10.10 *(57.58)*	3.74 *(21.35)*	3.30 *(18.82)*	0.39 *(2.25)*	17.53 *(100)*
D7	2.07 *(58.33)*	0.49 *(13.89)*	0.99 *(27.78)*	0 *(0)*	3.55 *(100)*
D8	0.39 *(53.33)*	0.25 *(33.33)*	0.10 *(13.34)*	0 *(0)*	0.74 *(100)*
D9	2.46 *(78.13)*	0.25 *(7.81)*	0.39 *(12.50)*	0.05 *(1.56)*	3.15 *(100)*
D10	0.39 *(26.67)*	0.74 *(50.00)*	0.34 *(23.33)*	0 *(0)*	1.47 *(100)*
D11	0.34 *(58.33)*	0.20 *(33.33)*	0.05 *(8.34)*	0 *(0)*	0.59 *(100)*
D12	2.27 *(68.66)*	0.59 *(17.91)*	0.44 *(13.43)*	0 *(0)*	3.30 *(100)*
D13	0.79 *(66.67)*	0.25 *(20.83)*	0.15 *(12.50)*	0 *(0)*	1.19 *(100)*
D14	2.07 *(63.64)*	0.39 *(12.12)*	0.74 *(22.72)*	0.05 *(1.52)*	3.25 *(100)*
D15	7.34 *(47.00)*	3.94 *(25.24)*	4.09 *(26.18)*	0.25 *(1.58)*	15.62 *(100)*
D16	1.82 *(42.05)*	1.48 *(34.09)*	0.99 *(22.72)*	0.05 *(1.14)*	4.34 *(100)*
D17	18.62 *(55.83)*	5.91 *(17.73)*	7.78 *(23.34)*	1.03 *(3.10)*	33.34 *(100)*
D18	0.15 *(25.00)*	0.39 *(66.67)*	0.05 *(8.33)*	0 *(0)*	0.59 *(100)*
D19	0 *(0)*	0.05 *(25.00)*	0.05 *(25.00)*	0.10 *(50.00)*	0.20 *(100)*
D20	1.38 *(50.91)*	0.74 *(27.27)*	0.59 *(21.82)*	0 *(0)*	2.71 *(100)*
Sum	54.93 *(100)*	21.33 *(100)*	21.67 *(100)*	2.07 *(100)*	100 ---

Note: All values are expressed in percentages according to the existing cases.
The upper value is considered with respect to the total of the set studied -2,030 cases-, and the value in brackets is considered with respect to the partial calculation of cases per type of damage.

Table 5 – Percentage of cases per type of damage and building typology

4. DISCUSSION

It is significant that, among the 20 types of damages, the four types of damages with more cases are those related to the presence of water (D6, D15, D16 and D17). This is a very important aspect to be considered, and the Basic Document on Healthiness of the Spanish Building Technical Code (CTE/DB-HS-1) (Ministerio de la Vivienda 2006) becomes important as it includes the design and execution conditions that should be respected in buildings in relation to the degree of impermeability, watertightness conditions, etc.

Considering the relationship of the original causes indicated in Table 1 can be useful to check how the singular points of facades, windows and roofs are treated (in both the project and execution), and generally, if the basic criteria of a good construction are considered (Carretero-Ayuso 2017) (Carretero-Ayuso 2018).

Generally, the specific development of pathology combinations (qualitative and quantitative interrelation between U/D/C) is not included in research studies, nor, based on these combinations, the possibility of presenting the general construction epidemiology of a country. The great difficulty of obtaining large datasets of damages not occurring in a concrete building/zone or in a building typology of which a specific aspect is to be studied is the main reason why the pathology combinations are not studied at a large scale. Providing its frequency and characterization from empirical and actual data is particularly something of a challenge. As this study used many data, the existing pathology combinations were deeply studied and analysed in the 5 construction units: these construction units corresponded to both the total of data in the study period and the total of territorial data in Spain.

The 5 dominant pathology combinations (see the terminology section at the end of the paper) were related to the presence of water, and their original causes were related to heterogeneities or constructive critical points of the envelope. According to all the information previously included in the Results section, the interrelations U1/D17/C4 (also identified as 'A') and U3/D6/C8 (also identified as 'G') were simultaneously recurrent, frequent, and dominant pathology combinations.

All this information could be of great interest to the technicians involved in the construction process (either in the project phase or in the execution phase), and their knowledge could be significantly helpful to pay attention to the most conflictive and pathology points, thus avoiding repeated errors, optimizing the operation of buildings, and contributing to their sustainability (Adabre et al. 2020).

There is no international study that uses a methodology whose sources of information are the complaints of the building owners, that is specified by expert's reports issued by qualified technicians or that analyses 100% of existing cases in a nation in the period studied. This dataset could therefore be understood as a 'radiography' that reflects the pathology state of current building envelopes in Spain. If this dataset is analysed in detail, greater security measures could be adopted in both the design of buildings and the site management to reduce the number of damages and deficiencies in the future.

This research study is also important as other research studies have analysed the effectiveness and opportunity of interviewing users/owners in relation to the presence of construction deficiencies in their dwellings, thus concluding that this is not a reliable method to compile data (Milion et al. 2017). Therefore, the origin and way of obtaining data in this study -as indicated in the methodology- is a realistic and optimal alternative to know the most important damages of these construction units.

Given the similarity of the construction units with respect to those from the rest of the European Union, the authors of this research consider that the results can be extrapolated to other countries as there is a common regulation that guarantees the free circulation of people and goods and the normalisation/standardisation of products.

5. CONCLUSIONS

Five construction units that belong to the external building envelope are studied, thus determining the damages and their original causes. The construction units with more cases are coated facades (U5= 29.75%) and flat roofs (U3=27.09%). The most present types of damages are 'infiltration humidity' (D17=33.35%), 'direct infiltrations of water and/or dripping (D6=17.54%) and 'condensation humidity' (D15=15.62%); moreover, D15 and D17 are the damages which occur in the 5 construction units. The original causes with a greater percentage presence are 'the absence or deficiency of sealing' (C4=14.38%), 'deficient disposition of waterproofing sheet' (C8=9.01%), and 'the existence of thermal bridges' (C23=7.98%).

Based on the analysis, 228 different types of pathology combinations are characterized (interrelation construction unit/damage/original cause). The most prevalent pathology combinations in each construction unit are due to the problems related to the presence of water (damages D6, D15, D16 or D17 are present). The most important interrelations are U1/D17/C4 (*window frameworks where damages of infiltration humidity caused by the absence or deficiency of sealing occurred)* and

U3/D6/C8 *(flat roofs where damages due to direct infiltrations of water and/or dripping caused by the deficient disposition of waterproofing sheet occurred)*.

Furthermore, the percentage value of the 20 types of damages has been breakdown and quantified according to the building typology in which they occurred, and the result is that 54.93% occurred in building blocks. Among them, the greatest concentrations are obtained in 'infiltration humidity' (D17=18.62%).

6. TERMINOLOGY

Construction unit: Each element which is part of the envelope of a building.

Primary damages: The damages whose individual weight within the general calculation is greater than 15%. There are 3, and their sum is 66.51% of the total. Among them, that obtaining the essential weight of the occasions (that obtaining the greatest value) is called 'critical primary damage', and the remaining are called 'basic primary damages'.

Secondary damages: The damages whose individual weight within the general calculation is greater than 2% and lower than 15%. There are 8, and their sum is 26.59% of the total.

Trivial damages: The damages whose individual weight within the general calculation is lower than 2%. There are 9, and their sum is 6.90% of the total.

Hyper-common original cause: The original cause which is in the first place. Its presence is greater than 10%, and there is only 1 among the 33.

Usual original causes: Their presence is between 5% and 10%. There are 4 original causes.

Occasional original causes: Their presence is between 2% and 5%. There are 11 original causes involved in this bracket.

Residual original causes: Their presence is lower than 2%. There are 17 original causes meeting this condition.

Pathology combination: It is the construction interrelation between the three descriptors (construction unit, damage, and original cause), so the type of damage in a certain construction unit and caused by a specific original cause is exemplified.

Different pathology combinations: Expression to emphasize the pathology combinations from the point of view of their diversity (different types of pathology combinations) and quantity (there are 228).

Recurrent pathology combinations: Each of the first 3 pathology combinations with a larger number of cases with respect to a construction unit. There are 15 in total.

Dominant pathology combinations: This is the most important pathology combination per number of cases within a construction unit. There are 5. They obtain a greater value among the recurrent pathology combinations.

Frequent pathology combinations: The pathology combinations that globally obtain most cases (regardless of the construction unit in which they take place). There are 2.

Groups of pathology combinations: The pathology combinations that share the same type of damage within a construction unit, only differing in the original cause causing them. There are 44 (34 in the vertical envelope and 10 in the horizontal envelope).

REFERENCES

Adabre, M. A., Chan, A. P., Darko, A., Osei-Kyei, R., Abidoye, R., Adjei-Kumi, T. (2020). "Critical Barriers to Sustainability Attainment in Affordable Housing: International Construction Professionals' Perspective". *J. Clean. Prod.*, 253, 119995.

Al-Sharif, L., Aal, O. F. A., Alqumsan, A. M. A., Abuzayyad, M. A. (2015). "The HARint Space: A Methodology for Compliant Elevator Traffic Designs". *Building Services Engineering Research and Technology*, 36(1), 34-50.

Alba Cruz, R. C., Cruz Álvarez, J. J., Posada, A. A. (2013). "Process Improvement in Quality Control for the Design of Waterproofing Systems in Buildings". *Revista de Arquitectura e Ingeniería*, 7(2), 1-57.

Andújar-Montoya, M. D., Marcos-Jorquera, D., García-Botella, F. M., Gilart-Iglesias, V. (2017). "A Context-Driven Model for the Flat Roofs Construction Process through Sensing Systems, Internet-of-Things and Last Planner System". *Sensors*, 17(7), 1691.

Azhar, S. (2011). "Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry". *Leadership and Management in Engineering*, 11(3), 241-252.

Bauer, E., Kraus, E., Silva, M., Zanoni, V. (2014). "Evaluation of damage of building facades in Brasilia". Proc., *XIII International Conference on Durability of Building Materials and Components*. Sao Paulo, Brazil, CIB-RILEM, 535-542.

Boudreaux, P., Pallin, S., Accawi, G., Desjarlais, A., Jackson, R., Senecal, D. (2018). "A Rule-Based Expert System Applied to Moisture Durability of Building Envelopes". *Journal of Building Physics*, 42(3), 416-437.

Carraro, M., and Oliveira, L. A. (2015). "Os impactos do processo de projeto na execução e desempenho da fachada". Proc., *IV Simposio Brasileiro de Qualidade do Projeto no Ambiente Construido*, Universidade Federal de Viçosa

Carretero-Ayuso, M. J., García-Sanz-Calcedo, J., Rodriguez-Jimenez, C. E. (2018). "Characterisation and Appraisal of the Technical Specifications in the Design of Brick Facades in Spain". *J. Perform. Constr. Facil.*, 32(3), 04018012/1-9.

Carretero-Ayuso, M. J. (2018). Technical Guidance Documents on Facades, 1st (may'18) Ed., *Musaat Fundation*, Madrid.

Carretero-Ayuso, M. J. (2017). Technical Guidance Documents on Roofs, 1st (may'17) Ed., *Musaat Fundation*, Madrid.

Carretero-Ayuso, M. J., García-Sanz-Calcedo, J., Reyes-Rodriguez, A. M. (2016). "Qualitative and Quantitative Analyses on Project Deficiencies in Flat-Roof Design in Extremadura, Spain". *Journal of Construction Engineering and Management*, 142(11), 04016061-1-04016061-7.

Carretero-Ayuso, M. J., and Moreno-Cansado, A. (2016). National Statistical Analysis on Construction Anomalies in Spain, *Musaat Foundation*, Madrid.

Conceição, J., Poça, B., de Brito, J., Flores-Colen, I., Castelo, A. (2019). "Data Analysis of Inspection, Diagnosis, and Rehabilitation of Flat Roofs". *J. Perform. Constr. Facil*., 33(1), 04018100-1-04018100-12.

Conceição, J., Poça, B., de Brito, J., Flores-Colen, I., Castelo, A. (2017). "Inspection, Diagnosis, and Rehabilitation System for Flat Roofs". *J. Perform. Constr. Facil.*, 31(6), 04017100.

Chong, W., and Low, S. (2006). "Latent Building Defects: Causes and Design Strategies to Prevent Them". *J. Perform. Constr. Facil.*, 20(3), 213-221.

Chou, J., Yang, I., Chong, W. K. (2009). "Probabilistic Simulation for Developing Likelihood Distribution of Engineering Project Cost". *Automation in Construction*, 18, 570-577.

Feitosa, R. C., and Wilkinson, S. J. (2020). "Small-Scale Experiments of Seasonal Heat Stress Attenuation through a Combination of Green Roof and Green Walls". *J. Clean. Prod.*, 250, 119443.

Filippín, C., and Flores Larsen, S. (2005). "Winter Thermal Behaviour of a Conventional House in Real Conditions of use". *Avances en Energías Renovables y Medio Ambiente*, 9, 05.67-05.72.

Garcez, N., Lopes, N., de Brito, J., Sá, G. (2012). "Pathology, Diagnosis and Repair of Pitched Roofs with Ceramic Tiles: Statistical Characterisation and Lessons Learned from Inspections". *Constr. Build. Mater.*, 36(0), 807-819.

Gaspar, K., Casals, M., Gangolells, M. (2016). "Classifying System for Façades and Anomalies". *J. Perform. Constr. Facil*, 30(1), 04014187-1/-04014187-10.

Gaspar, P., and de Brito, J. (2005). "Mapping Defect Sensitivity in External Mortar Renders". *Constr. Build. Mater.*, 19(8), 571-578.

Ger Lobez, F. (1898). Treatise of Civil Construction, 1ª Ed., *La Minerva Extremeña*, Badajoz.

Gonçalves, M., Lopes, J. G., de Brito, J. (2011). "Mechanical Performance of Lap Joints of Flat Roof Waterproofing Membranes Subjected to Artificial Weathering." *Exp Tech*, 35(3), 21-28.

Gonçalves, M., Lopes, J. G., De Brito, J., Lopes, G. A. (2008). "Mechanical Performance of Lap Joints of Flat Roof Waterproofing Membranes". *Exp Tech*, 32(1), 50-57.

Hradil, P., Toratti, T., Vesikari, E., Ferreira, M., Häkkinen, T. (2014). "Durability Considerations of Refurbished External Walls". *Constr. Build. Mater.*, 53, 162-172.

Ilozor, B. D., Okoroh, M. I., Egbu, C. E. (2004). "Understanding Residential House Defects in Australia from the State of Victoria." *Build. Environ.*, 39(3), 327-337.

Ko, K. P., Molleti, S., Bishop, M., Baskaran, A. (2006). SIGDERS Wind Uplift Resistance Data on Mechanically Attached Single Ply Roofing Systems – Effect of Steel Deck Parameters, National Research Council Canada, Institute for Research in Construction, Ottawa.

Koh, J., Ray, S., Hodges, J. (2017). "Information mediator for demand response in electrical grids and buildings". Proc., Semantic Computing (ICSC), 2017 IEEE 11th International Conference On, IEEE, 73-76.

Lee, D., Chi, H., Wang, J., Wang, X., Park, C. (2016). "A Linked Data System Framework for Sharing Construction Defect Information using Ontologies and BIM Environments". *Automation in Construction*, 68, 102-113.

Liu, W., Feng, Q., Chen, W., Wei, W., Deo, R. C. (2019). "The Influence of Structural Factors on Stormwater Runoff Retention of Extensive Green Roofs: New Evidence from Scale-Based Models and Real Experiments". *Journal of Hydrology*, 569, 230-238.

Love, P. E., Smith, J., Ackermann, F., Irani, Z., Teo, P. (2018). "The Costs of Rework: Insights from Construction and Opportunities for Learning". *Production Planning & Control*, 29(13), 1082-1095.

Love, P. E. (2002). "Influence of Project Type and Procurement Method on Rework Costs in Building Construction Projects". *J. Constr. Eng. Manage.*, 128(1), 18-29.

Meiss, A. E., and Muñoz, J. E. F. (2015). "Lesions and Rehabilitation of Plumbing and Sanitation Installations in Houses". *RE-Revista de Edificación*, 45, 143-151.

Milion, R. N., Alves, T. d. C., Paliari, J. C. (2017). "Impacts of Residential Construction Defects on Customer Satisfaction". *International Journal of Building Pathology and Adaptation*, 35(3), 218-232.

Mills, A., Love, P. E., Williams, P. (2009). "Defect Costs in Residential Construction". *Journal of Construction Engineering and Management*, 135(1), 12-16.

Ministerio de Fomento. (2015). The Commission for the Implementation of the BIM Methodology has been Formed, Ministry of Development, Madrid.

Ministerio de la Vivienda. (2006). "Construction Technical Code -Royal Decree 314/06- (Código Técnico de la Edificación: CTE)".

Misar, I., and Novotný, M. (2017). "Defects and behaviour of inverted flat roof from the point of building physics". Proc., 8th International Conference Building Defects 2016, EDP Sciences, Ceske Budejovice, Czech Republic, 02002/1-7.

Molnár, M., and Ivanov, O. L. (2016). "Clay Brick Masonry Facades with Cracks Caused by Corroding Bed Joint reinforcement–Findings from Field Survey and Laboratory Study". *Constr. Build. Mater*., 125, 775-783.

MUSAAT. (2015). Expert Records and Reports if Accidents in Spain, Mútua de Aparejadores y Arquitectos Técnicos, Madrid.

Olanrewaju, A. L. A., Khamidi, M. F., Idrus, A. (2010). "Quantitative Analysis of Defects in Malaysian University Buildings: Providers' Perspective". *Journal of Retail & Leisure Property*, 9(2), 137-149.

Olsson, L. (2018). "Rain Resistance of Façades with Façade Details: A Summary of Three Field and Laboratory Studies". *Journal of Building Physics*, 41(6), 521-532.

Park, S., and Song, S. (2018). "Case Study on the Inspection and Repair of Window Condensation Problems in a New Apartment Complex". *J. Perform. Constr. Facil*., 32(5), 04018071.

Pauwels, P. (2014). "Supporting Decision-Making in the Building Life-Cycle using Linked Building Data". *Buildings*, 3, 549-579.

Pereira, C., de Brito, J., Silvestre, J. D. (2018). "Contribution of Humidity to the Degradation of Façade Claddings in Current Buildings". *Engineering Failure Analysis*, 90, 103-115.

Piskoty, G., Wullschleger, L., Loser, R., Herwig, A., Tuchschmid, M., Terrasi, G. (2013). "Failure Analysis of a Collapsed Flat Gymnasium Roof". *Engineering Failure Analysis*, 35, 104-113.

Rodríguez de la Flor, Beatriz. (2015). "Descubriendo la Mediación". *Cercha*, 126 (October), 10-13.

Sá, G., Sá, J., de Brito, J., Amaro, B. (2015). "Statistical Survey on Inspection, Diagnosis and Repair of Wall Renderings". *Journal of Civil Engineering and Management*, 21(55), 623-636.

Sarman, A. M., Nawi, M. N., Che-Ani, A. I., Mazlan, E. M. (2015). "Concrete Flat Roof Defects in Equatorial Climates". *International Journal of Applied Engineering Research*, 10(3), 7319-7324.

SERJUTECA. (2015). Reports and Documents on Accidents Involving Professional Civil Liability of Building Surveyors and Technical Architects in Spain, Servicios Jurídicos Técnicos Aseguradores, Madrid.

Silva, R. R., Lopes, J. G., Correia, J. R. (2010). "The Effect of Wind Suction on flat Roofs: An Experimental and Analytical Study of Mechanically Fastened Waterproofing Systems". *Constr. Build. Mater.*, 24(1), 105-112.

Silvestre, J. D., and de Brito, J. (2011). "Ceramic Tiling in Building Façades: Inspection and Pathological Characterization using an Expert System. *Constr. Build. Mater.*, 25(4), 1560-1571.

The American Institute of Architects. (2013). "The business value of BIM in North America. multi year trend analysis and user ratings (2007-2012)". Proc., AIA AAJ National Conference: Alternative Project Delivery, McGraw Hill Construction, Portland (Oregon).

Walter, A., Brito, J., Lopes, J. G. (2005). "Current Flat Roof Bituminous Membranes Waterproofing Systems - Inspection, Diagnosis and Pathology Classification". *Constr. Build. Mater.*, 19(3), 233-242.