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Damage assessment of the May 31st, 2019, Talcahuano tornado, Chile

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ABSTRACT

On May 31st, 2019, a tornado hit the city of Talcahuano, Chile, generating significant damage to structures and leaving one person dead. The objective of the present paper is to report on damage to structures in Talcahuano. A preliminary survey was performed by the Municipality of Talcahuano and covered the entire affected area with a cellphone web application used to report the severity and distribution of damage. A more comprehensive damage survey was conducted in the *Brisa del Sol* neighborhood in the *Medio Camino* area by the UCSC team to assess the damage distribution within an area with well-defined and homogeneous building typologies. The results of the field surveys showed that the tornado behaved as a skipping tornado and that most damage to houses consisted of wall opening damage, roof sheathing failure, and wall cover removal (EF0), followed by partial roof removal (EF1). It was noticeable that self-built systems (house additions) were more damaged than original houses, which may be explained by the fact that such structures do not always meet minimum building standards. It is recommended that field surveys conducted by municipalities and the Ministry of Social Development consider typical damage types rather than just categories such as minor, moderate, or major. Finally, it is recommended that the feasibility of implementing mitigation measures such as stricter wind load provisions and dual-objective tornado design philosophy in the Concepción-Talcahuano area be analyzed.

1. Introduction

On May 30th and 31st, 2019, two destructive tornado events affected the cities of Los Angeles and Talcahuano, respectively, in the Biobio Region, Chile [1]. A preliminary analysis assigned an intensity of EF2 to the Los Angeles event and EF1 to the Talcahuano event, according to the Enhanced Fujita (EF) scale [2], which ranks tornado intensities based on damage to houses, trees, and cars [3] on a scale of EF0 to EF5. Despite the severity of the events, only one death was reported [4]. It was observed that the Talcahuano tornado was generated at sea and then moved inland in a fairly straight line for approximately 17 km over 15 min [3]. The maximum wind velocity was estimated to be 138–177 km/h, according to the Enhanced Fujita scale.

A tornado is a column of rotating air that extends from a cloud to the ground. Tornadoes are characteristic events in areas where warm and cold air masses of contrasting natures collide, resulting in the presence of wind gusts and instability. These phenomena typically occur over plains, with their paths spanning only few kilometers in length, and are often less than 100 m in width and short-lived [5]. They are typically observed in the United States (Tornado Alley), where tornadoes have become one of the most devastating natural hazards and there are 1200 events per year, on average [6,7]. Such hazards are less frequent in Chile, but they have been observed regularly over the years, mainly in rural areas. In fact, according to Bastías-Curivil [8]; at least 57 tornadoes have been observed in Chile since 1633, and most of them have occurred between the Ñuble and Los Lagos regions. The previous tornado observed in Concepción occurred on May 27th, 1934. The event crossed downtown from the Biobio River to the Nonguén Valley and left 27 dead and 599 injured, uprooted 30 trees in the main square, removed the roof of the city market, and damaged doors and windows of houses [8,9].

Despite the damage caused by tornadoes in various countries, tornado provisions are not always included in residential building codes

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since the probability of a tornado hitting one particular building in a given year is quite low [7]. Instead, regular wind loads are considered in residential building codes. However, regular wind loads from tornadoes differ greatly from conventionally conceived wind loads [10]. In fact, laboratory experiments showed that vertical uplift coefficients can be up to three times the value provided by design standards [10]. Moreover, wood-frame houses have performed poorly during tornadoes [6], even under loads generated by weak or moderate events [7]. Previous field surveys in the U.S. identified four typical failure mechanisms, namely, loss of roof sheathing, breaching of doors and windows, failure of roof-to-wall connections, and collapse of walls [6]. Tornado provisions are not included in Chilean standards for wind loads [11], either. The Chilean design code is based on the U.S. Standard (ASCE/SEI 7–05) and defines three methods for calculating wind loads acting on the main wind-resistant system and cladding of a building. Wind loads are estimated from the basic wind speed, which is the wind speed expected with an annual probability of 2%, extracted from a 50-year period of regional meteorological records. For Talcahuano and Los Angeles, the basic wind speed prescribed by the Chilean standard is 40 m/s, which can be increased to up to 56 m/s, equivalent to 202 km/h, due to site conditions.

Soon after the May 31st tornado event in Talcahuano, the authors conducted a field survey focused on structural damage to 1- and 2-story buildings. The objective of the present work is to report on damage to structures in Talcahuano. The paper is organized as follows: a brief description of the tornado is given in section 2, section 3 describes the methodology, and section 4 presents the results of the field survey. Sections 5 and 6 present the discussion and conclusions, respectively.

2. The May 31st, 2019, Talcahuano tornado

During the last week of May 2019, three consecutive extratropical cyclones hit the coast of the Biobio Region. The first one affected the region during the afternoon and night of May 26th. The second event entered the region the night of May 28th and stayed during the 29th. The post-frontal instability condition persisted on May 30th, and a tornado was observed in the city of Los Angeles. Then on May 31st the third cyclone arrived, which was generated between 30° and 40°S and moved from north to south with more significant wind shear than its predecessors, and a second tornado was observed, this time in Talcahuano. It was found that both of these tornadoes were generated by supercell thunderstorms and formed under similar synoptic-scale and mesoscale conditions [1].

According to the Chilean Meteorological Office (Dirección Meteorológica de Chile, DMC; [3], the Talcahuano tornado started shortly before 14:00 (18:00 UTC) off *Caleta El Soldado* and then moved in a southeast direction off the city of Talcahuano, almost parallel to the Concepción-Talcahuano Highway (see Fig. 1). From GOES-16 satellite images [3], it could be inferred that the cloud thickness reached up to 9.5 km above the Talcahuano area at 14:00 (18:00 UTC). In addition, the vertical temperature profile was in an unstable condition, with a completely saturated cloud column up to 2000 m. Furthermore, it was observed that wind gusts reached 54 km/h at a height of 1 km [3], which is often associated with tornado occurrence [12].

Interestingly, three weather stations were in the vicinity of the tornado's path in Talcahuano. These stations recorded both atmospheric pressure and wind velocity. The first station (CENMETEO in Talcahuano) measured a wind velocity of 50.7 km/h between 14:00 and 14:10. At the same time, the maximum wind velocity was found to be 101 km/h at the INPESCA station, while the Carriel Sur station (located at the airport, some 400 m from the tornado's path) recorded a maximum velocity of 91.5 km/h between 14:04 and 14:06. This information may be useful in providing lower bounds of wind speeds, as well as in calibrating the EF scale for different construction methods. It is possible to observe that the intensity of the tornado varied along the path, or that the tornado vanished and formed again as a skipping tornado. This variation of intensity may explain gaps in damage observed along its path. In addition, the intensity may be assumed to be higher at the center of the tornado compared to the observations at the weather stations. Fig. 1 shows the location of the study area and the tornado's path. The figure also shows the locations of the most affected neighborhoods, which are located within 40–150 m of the tornado's path.

3. Methodology

Talcahuano is a city that, due to geographical conditions and industrial activities, is exposed to both natural and anthropogenic hazards such as earthquakes, tsunamis, landslides, water pollution, oil spills, and industrial accidents, among others. Therefore, the Municipality of Talcahuano has developed several strategies to manage disaster risk. After the 2010 earthquake and tsunami, the local authorities formed the Department of Integrated Disaster Risk Management (Departamento de Gestión Integral del Riesgo, DGIR), which is responsible for planning, executing, and disseminating specific actions to reduce both natural and man-made disasters. In addition, the territory has been divided into six areas to provide more effective surveying and community assistance during emergency events. The areas are: (i) *Tumbes*, (ii) *Cerros*, (iii) *Centro*, (iv) *Salinas*, (v) *Higueras*, and (vi) *Medio Camino* (see Fig. 1). Even though tornado hazard has not been considered in the current risk reduction plans, the city is often affected by strong winds in winter. Therefore, the DGIR teams applied current protocols to survey the tornado-affected areas. After the event, several teams from the DGIR and UCSC (Universidad Católica de la Santísima Concepción) conducted a field survey to collect data on the damage within the tornado's path. The survey included expert observation, photos and aerial images taken by an unpiloted aerial vehicle (UAV) to capture the spatial distribution of damage (see Fig. 2).

The DGIR conducted a preliminary survey with the assistance of 155 volunteers from NGO ADRA Chile,[1] the Civil Defense and The National Youth Institute (Instituto Nacional de la Juventud, INJUV). This survey was carried out 24–36 h after the tornado, covered a total area of ~6 km^2, and sought to identify areas in which immediate assistance needed to be prioritized. Data were collected by means of a cellphone web application called Survey 123 for ArcGis. A typical form is shown in Supplementary Material. Not all volunteers had experience with damage assessment; therefore, one representative of the DGIR led a short training session on damage levels and the cellphone application. Two damage levels were used: major and minor. These damage levels were defined based on qualitative assessment. Major damage consisted of structural damage such as roof loss and damage to exterior walls, while minor damage was defined as loss of exterior wall cover, broken glass and/or damage to perimeter fences. In addition, volunteers could add a comment and a picture of the house in case it needed to be re-assessed. The main advantage of this survey was that all collected information was received in real-time by the DGIR, allowing local authorities a true understanding of the impact of the tornado in a short time.

After the preliminary assessment, the Ministry of Social Development (Ministerio de Desarrollo Social, MDS) applied the Emergency Basic Form (Ficha Básica de Emergencia, FIBE), employing the DGIR representatives and municipal staff, mainly social workers. A total of 850 questionnaires was applied to the entire affected area, which included the areas covered by the preliminary survey plus the *Centro*, *Cerros*, and *Tumbes* areas, at the same time home location coordinates were recorded by GPS. The survey was conducted from June 1st to 16th of 2019. This second survey, the FIBE form, is a self-declaration survey under technical supervision that aims to determine the need for social assistance, which is applied every time that natural or anthropogenic events require a response to protect life, goods, and the environment

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[1] https://adra.cl/.

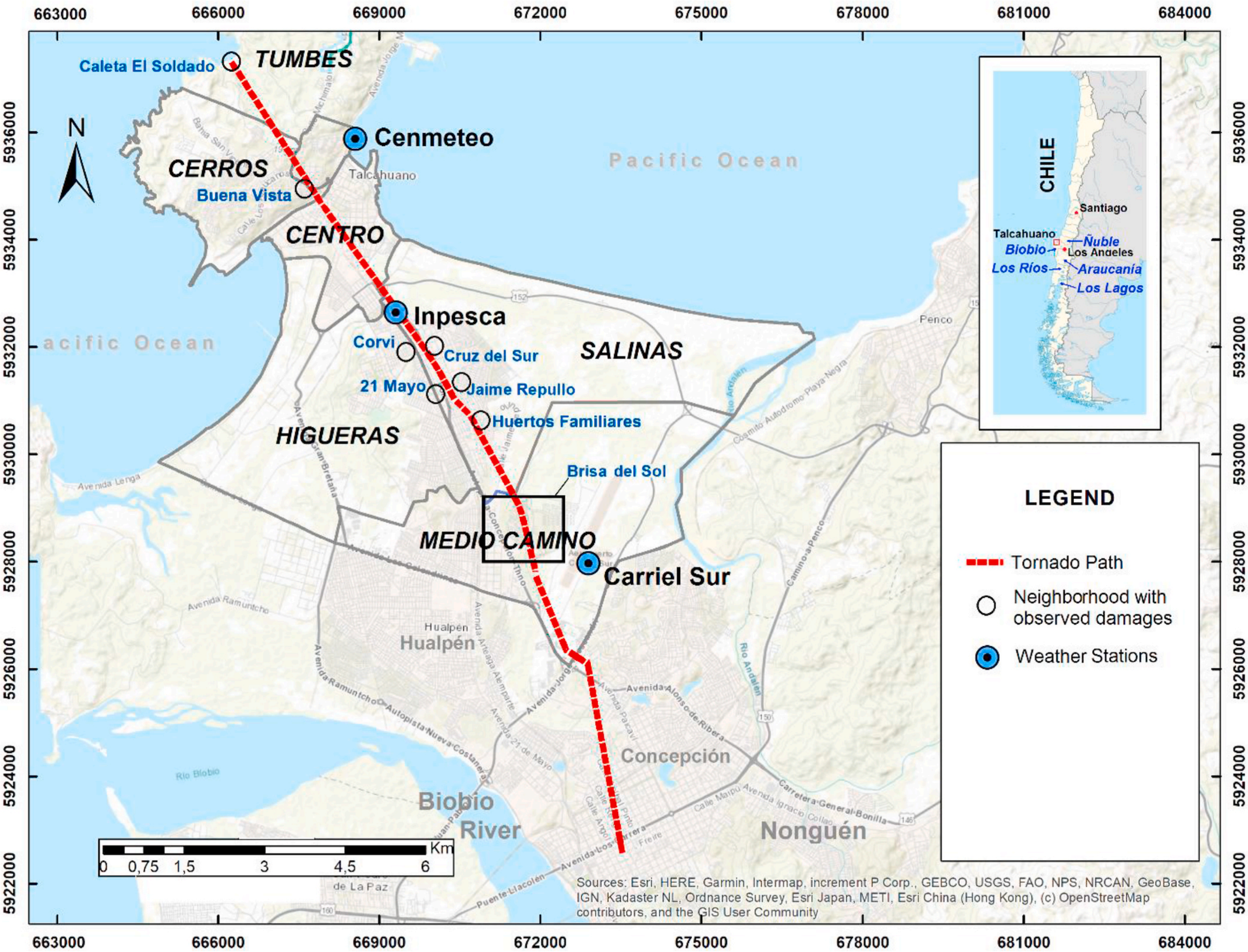

Fig. 1. Tornado path [3] and surveyed residential areas in Talcahuano.

[13]. The FIBE form collects information categorized into five topics: (i) address, (ii) family members, (iii) dwelling information, (iv) employment status, and (v) current needs, such as food, water, health care, clothes, and heating, among others. The dwelling information form collects specific information on the type of dwelling (apartment or house), type of home ownership (owners or tenants), utility services available (water, electricity, sewerage), damage to household items, damage to the home, and current residence after the event (the same house, a shelter, staying with relatives, the street). Moreover, the physical effects on the house are classified into five levels:

- No effects: no visible damage to the house.
- Less affected: minor damage is visible; however, residents have stayed in the house and do their activities in a pseudo-normal way.
- Moderately affected: damage is visible in several areas of the house, but it is still habitable, at least bedrooms and the kitchen. After minor repair, the house could be used normally in the short term.
- Very affected: it is not possible to use bedrooms, bathrooms, or the kitchen. The house is not habitable, and residents need to be relocated temporally. After a major repair, the home may be occupied again.
- Destroyed: damage is visible throughout the home. Residents must be relocated.

As in the preliminary survey, the damage levels were classified by means of a qualitative assessment. For this research, damage levels were re-grouped as minor, moderate, and major damage. The “no effect” level was not considered in this analysis. Minor damage corresponded to the “less affected” level, which included light damage to roof cover or exterior elements. Moderate damage corresponded to the “moderately affected” level, and consisted of broken glass, partial roof removal, and light damage to walls. Finally, major damage included both the “very affected” and “destroyed” levels, since both levels involved residents being relocated. This type of damage consisted of full roof removal and damage to structural walls. In addition, both minor and moderate damage can be grouped and compared to the minor damage of the preliminary survey, while major damage in both surveys may be equivalent.

A third field survey was conducted by the Ministry of Housing and Urban Development (Ministerio de Vivienda y Urbanismo, MINVU), with its construction and architecture professionals filling out another form named Ficha 2 MINVU. This form is a technical assessment of structures previously identified by the FIBE survey, i.e., 850 homes in total. It is an official document necessary to assign government funds, which are focused on reconstruction materials. The result of the Ficha 2 MINVU form is confidential and it was not available to the authors.

In parallel to the Ficha 2 MINVU, a fourth and more comprehensive damage survey was conducted on June 5th, 2019, by a team from UCSC in the *Brisa del Sol* neighborhood in the *Medio Camino* area. The aim of this survey was to determine the damage distribution within an area with well-defined and homogeneous building typologies. In contrast to the preliminary survey, the damage levels were classified as: (i) wall

Fig. 2. Example of aerial image along tornado's path in the *Brisa del Sol* neighborhood, Medio Camino area.

opening damage, (ii) roof sheathing failure, (iii) partial roof removal, (iv) full roof removal, (v) wall cover removal, (vi) partial wall collapse, and (vii) damage to house additions (usually built with no professional advice). Using GPS, the home location coordinates were also recorded. The observed damage was considered to classify the tornado's effects according to the Enhanced Fujita scale [2]. Damage associated with wall openings, roof sheathing failure and wall cover removal, as well as damage to house additions, was categorized as EF 0. Damage associated with partial roof removal was categorized as EF 1. Damage associated with full roof removal and partial wall collapse was categorized as EF 2. Based on the observed damage, EF3, EF4, and EF5 were not considered in this research.

4. Results

This section shows the results of the field surveys. First, the home typologies according to the Housing Encyclopedia[2] and the damage observed in each neighborhood are presented. Then the general damage distribution based on both the cellphone survey and FIBE form is shown. Finally, the results of the specific damage assessment in the *Brisa del Sol* neighborhood are presented.

4.1. Damage assessment in each neighborhood from FIBE forms

4.1.1. Cerros and tumbes areas

In the *Cerros* and *Tumbes* areas, 47 houses were reported damaged, mainly in the *Cerro Buenavista* neighborhood (14 damaged houses). Fig. 3 shows damaged houses in these areas. From Fig. 3-a, it is possible to observe the only damaged house in *Caleta El Soldado*. This house was made of lightweight materials such as timber and corrugated metal roof sheets, which is typical of traditional or outdated construction. The damage was not total, despite the type and material of the structure. Hence, it may be inferred that the wind velocity was not very strong when the tornado reached land. Fig. 3-b shows a representative house in *Cerro Buenavista*. This house was protected against the rain by a plastic cover since the wind removed the roof. In general, typical damage in this zone was concentrated in the wall opening (windows) and roof sheathing failure categories; therefore, the damage in this area was mainly classified as moderate (45%) and major (45%), with 5 houses reported as destroyed.

4.1.2. Centro and Higueras areas

Although the tornado crossed the entire area, only 10 buildings were identified with damage in the *Centro* area. As mentioned earlier, the Talcahuano weather station measured a maximum wind velocity of only 54 km/h. This area was less affected, probably due to the tornado having to cross *Tumbes* hill and its wind velocities decreasing. In general, according to the FIBE forms, the observed damage was reported to be moderate to major (80%), which implies broken windows, partial roof sheathing removal and light damage to wall cover sheathing.

Similarly, 17 buildings were reported damaged in the *Higueras* area. Most of the damage was observed in the *21 de Mayo* (7 damaged houses) and *Corvi* (3 damaged houses) neighborhoods (see Fig. 1). In this area it is possible to find one- or two-story timber houses. Fig. 4 shows typical houses and representative damage. Fig. 4-a shows houses with the roof sheathing uplift failure, typical for this entire affected area. As seen in the figure, this house was being repaired at the moment of the field survey (one day after the event). Fig. 4-b shows a structure, half of which experienced partial roof removal. Fig. 4-c and 4-d show houses with roof sheathing and wall opening failures, respectively. The observed damage in this sector was also classified as moderate to major (76%).

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[2] http://db.world-housing.net/list/?country=Chile.

Fig. 3. (a) Light structural damage in *Caleta El Soldado* and (b) the *Cerros* neighborhood.

Fig. 4. Damage observed in the *Higueras* area. (a) House with partial uplift of roof sheathing, (b) structure with partial roof removal, (c) house with roof sheathing failure, and (d) house with wall opening damage.

4.1.3. Salinas area

This mostly residential area sits on relatively flat land and is composed of several neighborhoods. A total of 571 buildings were reported affected in the entire area. The INPESCA weather station measured a maximum wind velocity of 101 km/h, but the wind intensity could have been higher at the center of the tornado. There were 211 damaged houses in the *Cruz del Sur* and *Las Rosas* neighborhoods alone. This area is made up of two-story houses built between 1970 and 1985. Originally, the house sizes were 60–90 m^2, with the ground floor made of reinforced masonry and the upper floor made of timber with a roof of fiber cement planks. Such confined or reinforced masonry structures are typical earthquake-resistant houses in Chile. However, most houses have been expanded, usually not in compliance with building standards. These additions maintained the use of reinforced or confined masonry on the ground floor and timber in the upper level, but corrugated metal sheets replaced the fiber cement planks. Fig. 5-a and 5-b show an example of the original and modified houses in the *Cruz del Sur* neighborhood, respectively. In both cases, it is possible to observe broken glass in windows, as well as wall sheathing and partial roof removal. It can also be observed in Fig. 5-a that steel fence panels were removed due to wind action.

Similarly, the *Jaime Repullo* and *Huertos Familiares* neighborhoods had a total of 215 structures damaged by the tornado. Various types of structures were observed in these areas. As in the previously mentioned neighborhoods, some houses built in the 70s are one- or two-story buildings made of timber. Fig. 5-d shows an example of damage to these structures, in which not only sheathing and partial roof failures were observed, but also full roof removal. In recent years, new structures have been built in the *Jaime Repullo* neighborhood, including two-story buildings inside gated communities. These houses have ground floors

Fig. 5. Damage observed in the Salinas area. (a) *Cruz del Sur* neighborhood, (b) *Cruz del Sur* neighborhood, (c) *Jaime Repullo* neighborhood, and (d) *Huertos Familiares* neighborhood.

built on confined masonry and upper floors constructed on lightweight steel framing. In general, these structures experienced less damage (wall and roof sheathing failure), although severe damage to utility poles was observed, as shown in Fig. 5-c.

In the *Salinas* area, 23% of the affected houses had damage classified as minor (light damage to roof cover or exterior elements), 39% had moderate damage (broken glass, partial roof removal and light damage to walls), and 38% presented major damage (full roof removal and extended damage to external walls).

4.1.4. *Medio Camino area*

In the *Medio Camino* area, only the *Brisa del Sol* neighborhood was affected, including the *Marina del Sol* Casino. This neighborhood is located west of *Carriel Sur* airport (see Fig. 1). According to the FIBE forms, a total of 205 structures were reported damaged; 14 were classified as destroyed, 62 as severely damaged (full roof removal and extended damage on external walls), and 89 as moderately damaged (broken glass, partial roof removal and light damage to walls). This neighborhood is a relatively new development – composed mainly of two-story houses with three well-standardized building models – that offers a good opportunity for assessing the damage severity distribution. These houses were built on a ground floor made of confined masonry and an upper floor made of lightweight steel framing. In addition to the houses, a group of four five-story reinforced concrete buildings, which experienced mostly roof sheathing failure, was also affected (not reported in this paper). A directional procedure method for design of the main wind force resisting system is applied in Chile, which is similar to the method used in Ref. [14]. Fig. 6-a, 6-b, 6-c, and 6-d show typical roof sheathing failure of this type of structure. However, in some cases the roof deck was removed together with the roof joist (Fig. 6-b and 6-c), while in other structures glass broke in doors and windows (Fig. 6-d). Few cases of severe damage such as full roof removal and wall openings were observed (Fig. 6-e). The damage to house additions such those shown in Fig. 6-f and 6-g is interesting. While there was no or minor damage to the original houses, the additions experienced partial uplift of the roof deck (Fig. 6-g) or partial wall collapse (Fig. 6-f). In general, these additions were built without regard for building standards or professional advice and with materials that differed from those used in the original house.

4.2. *Damage distribution according to cellphone surveys and FIBE forms*

This section describes the general damage distribution obtained from the preliminary field survey. While the FIBE form survey was applied throughout the area, the cellphone survey was applied to the most affected areas only. Fig. 7 shows a general view of the damage observed in Talcahuano along the tornado path. A fair level of agreement can be observed between the two damage distribution maps presented in Fig. 7, despite the different damage scales used in the surveys. It can be seen that major damage levels are concentrated along the tornado path.

In general, Fig. 7-b shows that the most affected areas are *Salinas* and *Medio Camino*, while *Centro* and *Higueras* each presented fewer than 20 damaged houses. The *Tumbes* area did not present any damage, except for the affected house in *Caleta El Soldado*. It is interesting that houses in areas neighboring the INPESCA weather station, which is located along the tornado path and recorded a maximum wind velocity of 101 km/h, did not present significant damage. Therefore, most of houses in these neighborhoods were able to resist the wind load despite being old and made of timber (see Fig. 4). However, the tornado intensity increased as it moved southeast. Damage to houses consisted mainly of wall opening and roof sheathing failure and wall cover removal, which is consistent with EF0 [3]. However, damage such as partial roof removal was also observed in several neighborhoods (*Jaime Repullo*, *Huertos Familiares*, and *Brisa del Sol*), which corresponds to EF1. Very few structures, such as the ones shown in Fig. 5-d and 6-e, experienced full roof removal or partial wall collapse (EF2). In addition, it was observed that recent structures (built after the 90s) performed better than old structures (built in the 70s and 80s) in the Salinas area. While the former group consists of houses made of confined masonry and lightweight steel framing with no modifications, the latter homes are made of timber with significant modifications to the original structure. In a similar manner, houses in the *Brisa del Sol* neighborhood, which are also made of

Fig. 6. Affected structures in the *Brisa del Sol* neighborhood. (a) Roof sheathing failure, (b) roof sheathing and joist failure, (c) roof sheathing and joist failure, (d) roof sheathing and wall opening failure, (e) complete roof failure, (f) partial wall collapse of house addition, and (g) roof deck uplift of house addition.

confined masonry and lightweight steel framing, showed a better performance than old houses in the *Salinas* area.

4.3. Damage distribution in the Brisa del Sol neighborhood

The comprehensive damage assessment conducted by the UCSC team included a total of 366 houses, of which 146 were found to have some degree of damage. The results of this analysis are presented in Fig. 8. Fig. 8-a shows the area affected by the tornado and the severity of the damage, 91.8% of which is classified as EF0, with only 11 houses undergoing damage classified as EF1 (7.5%) and just one – the house that suffered full roof removal – damage classified as EF2 (0.7%); this house is shown in Fig. 6-e. It is important to mention that EF0 and EF1 are related to damage to non-structural components, which are designed under conditions other than tornado loads. It was observed that the primary reason for damage was failure of anchor of non-structural components. In addition, it is worth mentioning that the house shown in Fig. 6-e had been modified for conversion into a local shop, with two large gates added to the ground floor. Subsequently, suction forces may be increased compared to neighboring structures.

Fig. 8-b presents the damage distribution according to the type of damage observed during the survey, with roof sheathing and wall opening failure being the most common problems, followed by wall cover removal, partial roof removal and damage to additions. In general,

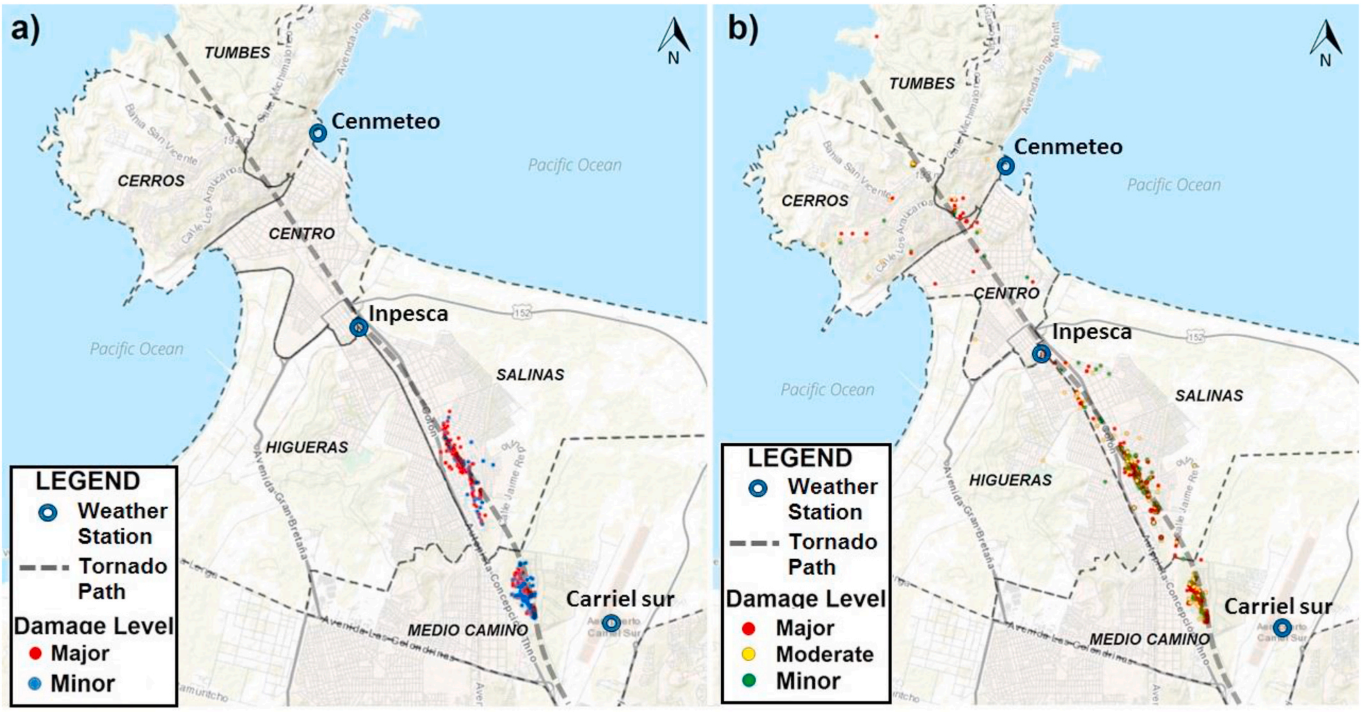

Fig. 7. Spatial damage distribution maps. a) Results from quick initial assessment with cell phones. b) Official survey with FIBE forms.

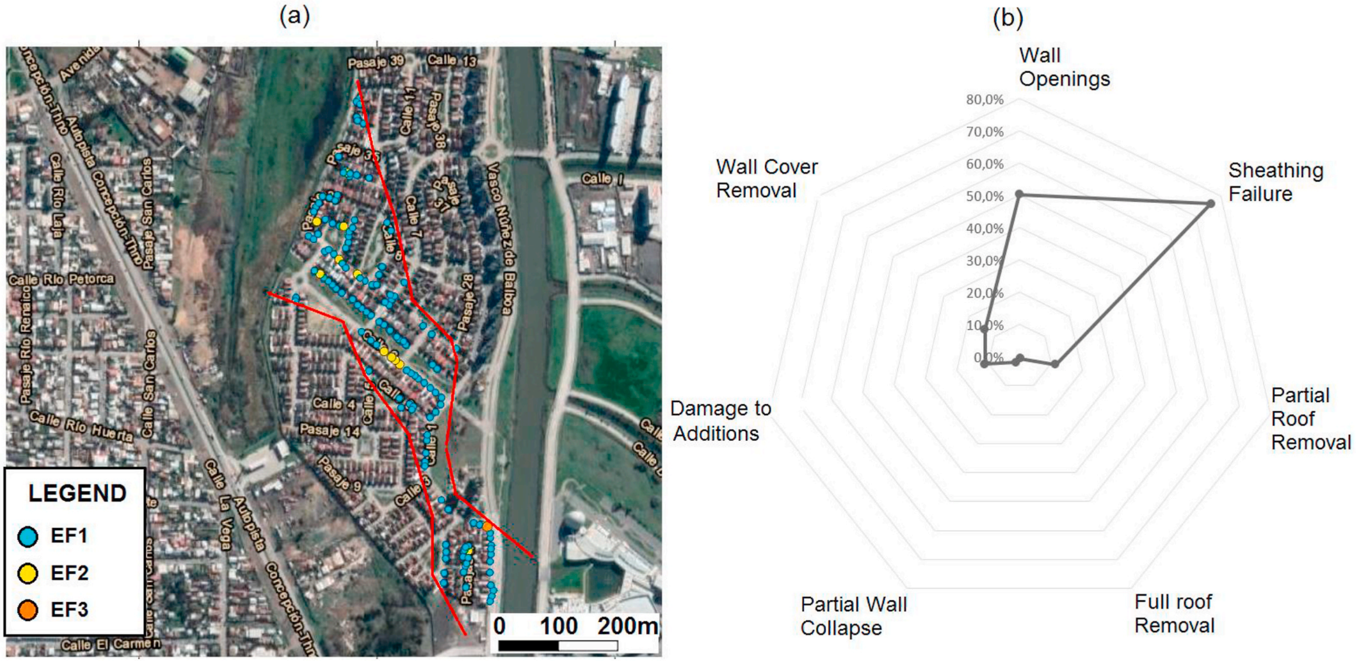

Fig. 8. (a) Damage surveyed in the *Brisa del Sol* neighborhood. Red line indicates the width of the tornado path. (b) Relative distribution of observed damage.

the structures in the *Brisa del Sol* neighborhood are similar to structures such as those in damage indicator 2 in TTU-WISE [2], which corresponds to one- or two-family residences (FR12); therefore, under normal conditions, this type of structure may be more resistant than old houses in other neighborhoods. Normal conditions are understood as a lack of glaring weak links, along with appropriate building materials, compliance with local building codes, and adequate maintenance [2]. Nevertheless, it is interesting that several additions, which usually do not comply with building standards, were more damaged than the original houses (see Fig. 6-f and 6-g).

5. Discussion

During the May 31st tornado, local observers reported short-term lifting of the tornado from the surface, suggesting that it was a skipping tornado [15]. In addition, the observed damage to structures presented gaps along the tornado's path, which is indicative of variable intensity along the path. It is accepted that for a tornado to be classified as a skipping tornado, the maximum gap size is typically 8–16 km, while larger gaps indicate two or more successive tornadoes [16]. The entire tornado path on May 31st was 17 km; therefore, the gaps were much smaller than the maximums for skipping tornados. Both tornadoes in Talcahuano and Los Angeles moved in a northwest to southeast direction, however, the 1934 Concepción tornado followed a path from southwest to northeast. In addition, observations of previous tornadoes in southern Chile do not include a clear description of their trajectories [8]. Therefore, it is not possible to define a typical trajectory of tornadoes in Chile. In addition, most tornadoes in South America have been observed in northern Argentina and southern Brazil [17,18]. Nevertheless, since no official tornado records exist [19], it is difficult to have accurate information on the intensity and path of past events. Moreover, the topography of the Andes may have affected the low-level jet via flow blocking, and more research is needed to understand tornado formation in areas with complex topography [1].

The damage survey carried out by the municipality soon after the event using cellphone apps proved to be in fair agreement with results from the FIBE forms (Fig. 7). The cellphone survey was carried out in 12 h with 155 volunteers and allowed a quick emergency response from DGIR representatives. However, this result needs to be analyzed with caution, due to the fact that only the most affected areas were surveyed and different damage levels were used. Moreover, the lack of experience of volunteers could have led to misjudgments on the damage to a given house. The results of the preliminary survey are also in good agreement with the more technical field survey conducted by UCSC in the *Brisa del Sol* neighborhood (Fig. 8). The main difficulty in analyzing results from the cellphone, FIBE, and UCSC surveys lied in combining different criteria and damage levels, which were developed for different purposes. Damage surveys are a critical component of the disaster management cycle because they contribute to both risk reduction and preparedness [20]. During this research, it was found that three governmental institutions (Municipality, Ministry of Social Development and Ministry of Housing) applied their own surveys for three different purposes. Unfortunately, this is a common practice in Chile not only for tornadoes, but also for other events such as earthquakes and tsunamis. None of the surveys provided a precise description of the degree of damage for a given damage indicator due to tornados [2]. Therefore, since tornado events have been observed regularly over the years, mainly in southern Chile, it is recommended that international protocols for tornado field surveys be adopted in Chile in order to optimize field work and avoid the duplication of efforts. Such field surveys may also be applied to winter windstorms, which are more frequent than tornadoes. Thus, the use of cellphone applications by the Municipality of Talcahuano was a step in the right direction, since sophisticated technologies such as mobile devices and volunteered geographic information further improve the damage-surveying process [20]. However, it would be more efficient for field surveys after windstorms or tornadoes to consider proper damage indicators and degrees of damage [2], rather than just categories such as minor, moderate, or major. Moreover, it would be beneficial to include quantitative measures such as the percentage of wall openings or percentage of roof cover removal to better classify different damage levels. Otherwise, it could complicate the estimation of resources needed for the reconstruction stage and to be prepared for the next event.

Since the tornado event in 2019, requirements to update protocols to deal with tornado issues have been adopted by the Communal Committee of Talcahuano. Thus, the DGIR has proposed improvements to the available equipment to carry out field surveys and transmit the information from the same affected areas, reducing the need for processes such as transcription of information. Another challenge is that the DMC and National Emergency Office (ONEMI) monitor weather conditions that precede tornado formation, with the two agencies meeting and determining the type of warning to be issued to local governments. These warnings will allow the DGIR planning the emergency response and defining one or several operation centers to collect and send the information in real time, thereby accelerating the delivery of resources to affected householders. During 2020, two tornado warnings have been issued that turned out to be false alarms, creating confusion in the population. Therefore, another challenge is to improve the warning system to be more assertive with adequate models and equipment.

It is important to consider that most of the affected neighborhoods, except *Brisa del Sol*, consisted of old timber houses that are not always in normal conditions [2]. Therefore, the EF Scale rating (and wind velocity bounds) could be overestimated. Since *Brisa del Sol* is a relatively new neighborhood, the structures there are well-designed and maintained. This house type is similar to that in damage indicator FR12 [2]; therefore, the EF scale may be more accurate in this area. Several houses presented a degree of damage 4 (uplift of roof deck and significant loss of roof covering material, according to TTU-WISE [2], which means a wind velocity in the rage 156–186 km/h (97–116 mph). The information provided by FIBE makes it difficult to determine the origin of roof failures. However, field observations made by the UCSC engineers team indicate that these failures were produced by a rapid pressurization due to wind moving through openings and not by impacts of other objects. Testimonies of affected residents and the small number of light personal items in the area confirmed this hypothesis. However, numerous instances of damage to non-structural components or additions built without engineering advice and minor damage to structural components were observed, which has also been reported in other events [21]. This may be due to the sum of two factors:

- The physical characteristics of the tornado differed greatly from the conventionally conceived atmospheric boundary layer [10] used in wind load designs established in Chilean and U.S. standards, such that the tangential velocity may have been higher than the maximum design velocity. In fact, tornado-like vortices can generate load coefficients that can be 10–50% greater than the standard provisions [10,22]. Additionally, the suction forces of a tornado are higher than those conventionally considered in structural design standards due to the low pressure. In fact, the vertical uplift coefficients can reach up to 3 times the wind load provisions [10].
- The performance of modified structures and additions built without engineering advice (both structural and non-structural elements) was poor. This non-engineered construction method is usually focused on minimizing costs but underestimates the importance of safety factors such as anchor dimensions and quantity, connection design, and distribution of structural and non-structural building elements. In fact, anchor failures of non-structural components and structural component coatings were among the main failures in all affected structures, showing the importance of structural systems to transfer the wind load from the roof to the foundations [23]. It is recommended that stronger roof-to-wall connections be used to maintain the structural integrity of the roof diaphragm and thus ensure the structural integrity of a house during a tornado [6].

It is important to note some differences between structures in the United States and Chile that may lead to under- or overestimation of wind velocities due to a tornado. For instance, the roof structure in Chilean houses, with roof cover applied directly to purlins/rafters, may be more susceptible to uplift than houses in the United States. Therefore, tornado wind velocities may be overestimated for a degree of damage equal or lower than 4. By contrast, since Chilean houses are designed against earthquakes, the structural walls may be more resistant than those in houses in the tornado area of the Unites States; therefore, wind velocities may be underestimated for a degree of damage 6 (most walls remain standing) and above (exterior walls collapsed [2]). Thus, future research on calibration of wind velocity ranges for different degrees of damage and adjustments of the EF Scale rating for local construction is an important matter.

Finally, it is necessary to analyze the need to implement tornado mitigation measures in southern Chile, as various events have been recorded there in the last 400 years [8]. Even though tornadoes in Chile are neither as frequent nor severe as those in the U.S. or Canada, the last two events (1934 and 2019) generated significant damage and casualties in the Concepción-Talcahuano area [3,4,8]. In addition, it would be important to study extreme weather conditions in a sub-seasonal context in Chile to provide information on the predictability of future similar events [1]. However, the implementation of mitigation measures requires a proper tornado hazard assessment. This assessment may be applied to an individual structure in the event of a single tornado [24–26], a whole region [5,7], or even considering a probabilistic tornado outbreak approach [27]. In the case of the Concepción-Talcahuano area, a tornado hazard assessment of the whole city or at community level is recommended [7,26], as the probability of a tornado hitting one particular building would be extremely low. An example of mitigation measures is the implementation of stricter wind load provisions for non-structural components in tornado-prone areas. The building code should be considered as a minimum requirement, since resulting structural improvements could reduce the level of damage and thereby mitigate economic losses and improve safety [28,31]. However, design against even the most severe tornadoes is not economically possible, and the dual-objective tornado design philosophy [29] may be a suitable approach to improve the structural performance of houses exposed to EF0 to EF2 tornados and protect human lives in the event of EF4 and EF5 tornadoes, assuming total destruction of the main structure but considering alternative protection approaches such as safe rooms or underground shelters. This philosophy is similar to the recently proposed classification of tsunami events as level 1 and level 2 [30]. The former has a recurrence period of several decades, and tsunami mitigation structures such as breakwaters, seawalls, and river gates may be effective at protecting properties against them. However, the latter has return periods of several hundred or thousand years, and hard measures would be completely meaningless and would not reduce the tsunami impact; therefore, soft measures such as tsunami awareness and evacuation to high areas inland would be preferable to safe human lives.

6. Conclusions

This paper presented an assessment of damage due to the May 31st, 2019, tornado in the city of Talcahuano. The field survey showed that the tornado behaved as a skipping tornado, which explains the different damage levels along its path. In general, most damage to houses was found to be wall opening damage, roof sheathing failure, and wall cover removal (EF0), followed by partial roof removal (EF1), while a few houses presented full roof removal (EF2). It was observed that wind load provisions in Chilean standards consider higher wind velocities than those measured during the tornado event. Therefore, damage to houses may be due to different physical characteristics of tornadoes. In addition, it is noticeable that modified structures and house additions built without engineering advice were more damaged than original houses. This may be because the additions do not always meet minimum building standards.

Southern Chile has been affected by tornadoes regularly in the last 400 years – the extent of written records – and the Concepción-Talcahuano area has experienced two significant events (EF1-EF2) in the last hundred years. Therefore, it is recommended that the feasibility of probabilistic tornado hazard assessment at a regional level be analyzed in order to implement mitigation measures such as stricter wind load provisions for non-structural elements in high tornado hazard areas under a dual-objective design philosophy. Moreover, field surveys conducted by official institutions after windstorms or tornadoes should consider proper identification of Damage Indicators (DI) and corresponding Degree of Damage (DoD) rather than just categories such as minor, moderate, or major. Finally, further research on tornado hazard under a climate change scenario would be useful for defining the potential intensity and recurrence of possible future events.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2020.101853.

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