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Alessio Pipinato

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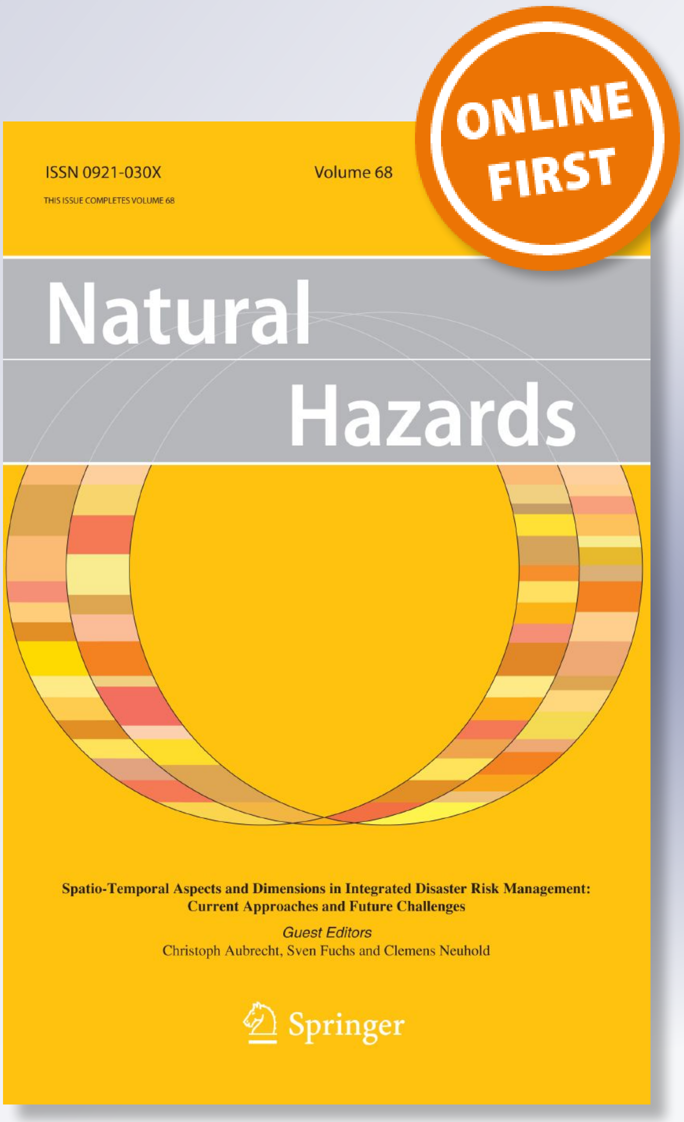

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ORIGINAL PAPER

Recent northeast Italian tornado events: lesson learned for improving structures

Alessio Pipinato[1]

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Abstract Increasing intensity and frequency of tornadoes have been reported in Europe in the last decades, and in Italy, in particular in the northeast area, including Veneto, Friuli Venezia Giulia and Trentino Alto Adige. The public consciousness and the meteorological control of this risk are sufficiently established in the USA. The European continent and the northeast of Italy do not exhibit a similar state, although the tornado damages induced are increasing and becoming of economic relevance. Studies and research are diffused and have reached a detailed level, being able to correlate tornado intensity to a detailed damage state for a wide amount of building classes. But, codes and standard, both in USA and in the whole European continent, have not been developed for tornado loadings. For this reason, to fill the gap between studies, research and observational data, in this study Italian wind extreme events are presented and discussed first. In a second part, the damage assessment results of the most extreme events recorded in the northeast of Italy (from F3 to F5, Fujita scale) from 1905 to 2017 are presented. Codes and standard showing the lack of design and verification procedure are presented in the third part. Finally, a tornado-resistant building classification is presented to enforce the consciousness that new codes and standard could protect people from extreme events, decreasing dramatically the devastation of not so rare phenomena also for Italy.

Keywords Tornado · Damage assessment · Natural hazard · Structural safety

✉ Alessio Pipinato
info@pipinatoandpartners.it

[1] AP&P, Minadois Street 20th, Rovigo, Italy

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1 Introduction

The European continent is not free from tornado events. While in the USA, some 1.200 tornadoes could be observed annually (ESWD 2017), in the European continent only 300 events every year are recorded (ESWD 2017). Europe experienced less frequent events than USA, but, e.g., storms can be really devastating: e.g., the Kyrill event in 2007 in UK and in Germany—(ESWD 2017; Groenemeijer et al. 2017; Fink et al. 2009); Poland and the North of France in 2008 (ESWD 2017); in 2015, Mira in Italy was hidden by a violent weather event (ESWD 2017). As a fact, the whole European continent effectively has experienced both tornadoes and violent events recently, as reported by the ESWD (2017). Recent studies dedicated to the European continent deals with the societal impacts of severe thunderstorms and tornadoes (Doswell 2003), with the severe convective storms in the European societal context (Doswell 2015), or with the social and economic impact of tornadoes in Europe analyzed using tornado reports from the European Severe Weather Database between 1950 and 2015 (Antonescu et al. 2017). Concerning the research, while many studies have been performed in the USA (Wegener 1917; Dotzek et al. 2008; Doswell et al. 2009) in Europe a little interest is growing recently particularly in Central Europe (Dotzek 2001, 2003; Dotzek et al. 2008), due to the large number of events reported in a hundred of observations, from 1905 to 2017 (Fig. 1). Concerning the Italian

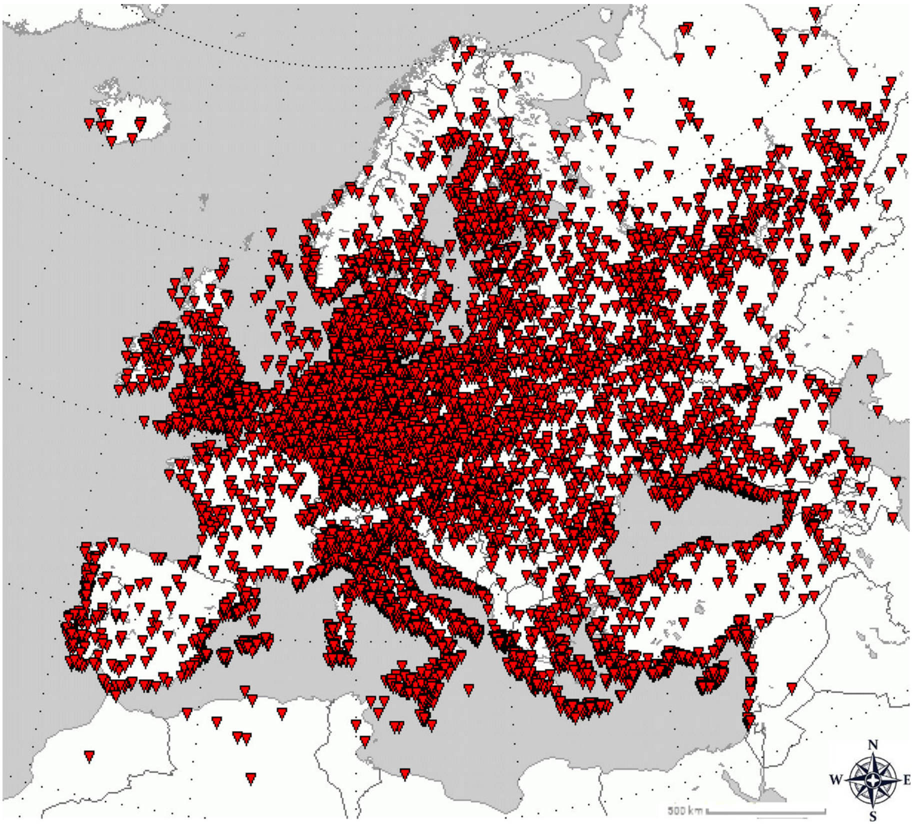


Fig. 1 Tornadoes recorded from 1905 to 2017 in Europe, 10.447 recorded events (ESWD 2017)

zone, even if the tornado problem is well-known, the most of studies, codes, standards and investment deals with the seismic risk. This is reasonable, because the seismic damage of the last century (1900–2000) in Italy summed up billion of euros, while the extreme wind events in the same period dozens of euros (Protezione Civile Italiana 2018). Concerning Italy, the most works available in the literature deals with the description of the local events (Bechini et al. 2001; Bertato et al. 2003), neglecting the structural damage induced to common building types (masonry one or two stories buildings) and the capacity of different building type to resist against tornadoes. Other studies deal with recent high impact events and are of interest because they explain the climatology of tornadoes in Italy: i.e., Antonescu et al. (2016) dealt with tornado observations across Europe between 1800 and 2014 and is used to produce a pan-European climatology; based on the tornado-occurrence datasets and articles published in peer-reviewed journals, the evolution and the major contributions to tornado databases for 30 European countries were analyzed. In this context, the contribution of this paper is (a) to study the tornado hazard and the effects of the most relevant wind-induced extreme events occurrence on residential and commercial buildings, through the analysis of the last recorded EF3–EF5 events in the northeast of Italy from 1905 to nowadays and (b) to report the capacity observed of specific class of buildings to resist against specific tornado events.

A research about historical tornado events is presented in the first part of this study, to provide relevant information for tornado hazard assessment in the northeast of Italy, as this is one of the most prone regions (Fig. 2). In the second part of the paper, the damage assessment of the buildings hit by the 1905–2017 events of the northeast of Italy is presented, providing building rating by means of a damage observational index. Observed damage is described in detail, analyzing the structural types involved and the presence of weak/vulnerable elements. In the third part, structural codes and common vulnerabilities are discussed. Finally, in the fourth and last section, a tornado-resistant building classification is presented basing onto the analysis of hundreds of records of northeast of Italy events analyzed in the study.

2 Wind-induced extreme events in the northeast of Italy

Storms occurred when warm humid air near the surface lay under drier air aloft with temperature decreasing rapidly with height, providing energy for the storms through the production of instability. Large changes in wind with height ("wind shear") over both shallow (lowest 1 km) and deep (lowest 6 km) layers—combined with the instability and high humidity near the surface—created a situation favorable for tornadoes to form (Schultz et al. 2014). In the USA, the large and extensive Midwestern American areas are an incredible basin that in summer fills with hot air and humidity, provided by Mississippi and its affluent as well as the Gulf of Mexico; the drier air comes from Canada, providing energy for the storms through the production of instability. The northeast of Italy is often the place in which cold air from the Atlantic sea coming from the Alps encounter warm air coming from the Adriatic Sea and from the African zone, causing widespread intense severe thunderstorms across the plains of northern Italy. Extreme event in the northeast of Italy includes: in 1930 a tornado took away the church of Selva del Montello (Treviso province) and was later classified as F5; this is the most intense phenomenon documented in the whole Italy. In 1970, a tornado started from the Euganean Hills and after several miles eastward came to the lagoon of Venice where it brought death and destruction. It was

Fig. 2 Tornadoes recorded from 1905 to 2017 in Italy, 1.323 recorded events (ESWD 2017)

ranked F4, and therefore the same level as Moore's tornado Fujita scale on May 20, 2013, in Oklahoma. Recently, there have also been relevant tornados that uncovered roofs, felled trees and destroyed entire buildings, as for example, the tornado of Riese Pio X of June 6, 2009, ranked F3, or that of July 8, 2015, Mira-Dolo this last ranked F4. Going over in the past, two devastating tornadoes occurred in Venice, respectively, on August 9, 1440, and August 5, 1657, and later a tornado that damaged the Saint Anthony church and the Ragione Palace in Padova on August 17, 1756 (Aglietti 1793). However, a relevant number of tornadoes took place in the Po valley (northeast Italy), which is a flat region prone to this kind of events: according to Selvini and Tibaldi (1995) and Giaiotti et al. (2007) a hundred of extreme wind events have been recorded in this area in the last century. A strong tornado was recorded in Padova on July 20, 1686 (Montanari 1694). Other dangerous events took place around the Garda lake, a waterspout on July 8, 1843 (Giornale dell'I.R., ILSLA, 1843); and around the city of Venice (September 11, 1970, F4 tornado). Consequently, it is possible, though rare, that an event similar to that in Oklahoma may also occur in the northeast of Italy (ARPAV 2016), and for this reason prevention measure is needed.

3 Historical catalogue

The northeast of Italy is prone to severe atmospheric events, including tornadoes and downbursts: an historical review of past events occurred in the three Italian regions composing the territory called northeast (Veneto, Friuli Venezia Giulia and Trentino Alto Adige) is herein presented. Recent studies include also the Emilia Romagna region, which is outside the northeast region and also not homogeneous with the meteorological data of the northeast of Italy, and that for this reason has been neglected. The Trentino Alto Adige information has also been excluded, as in this region low-intensity phenomena have been recorded. A complete list of events from 1884 to 2017 is reported in Table 1. While Fig. 3 gives an overview of tornado from 1905 to 2017 with the intensity information in Fujita scale, Fig. 4 shows more than 200 tornadoes and severe wind occurrences in the northeast of Italy area on the basis of the data provided by ESWD Catalogue (Dotzek et al. 2009) and compared to historical documents in the range 1905–2017. In this time range, 1884–2017, one main event ranked in the Fujita scale (Fujita 1971) as F5 has been found, and occurred in 1930 in Selva del Montello (23 victims and more than 110 people injured) with along path of more than 60 km (Dotzek et al. 2009); two events in the Venice inland ranked F4, respectively, in 1970 and 2015; three events ranked F3 occurred in the Po valley (Rovigo province) and in Riese Pio X (Treviso province). The intensity of tornadoes occurred in the northeast of Italy and evaluated according to the *F*-scale are shown in Fig. 5: as evidenced, most of them (67%) is characterized by limited intensities, i.e., F0–F1 (Dotzek et al. 2009). The spatial distribution of the intensity of recorded damages is reported in Fig. 6: recorded events are almost uniformly distributed within the investigated area, not highlighting sites of interest. Time annual distribution has been reported in Fig. 7: most of them occurred during June, July and August, in good agreement with results derived by Dotzek (2001), Holzer (2001) and Bissolli et al. (2007) for other European areas. The time-year distribution is reported in Fig. 8: an increasing number of records is probably also correlated with the increasing observational documents available in the last period.

4 Tornado intensity estimations

To estimate the tornado intensity, the damage survey is a well-known procedure for the assessment, as direct measures of this extreme event are rather difficult and rare. As a matter of fact, less than one hundred near-ground scientific measurements were documented between 1894 and 2015 all around (Karstens et al. 2010; Kato et al. 2015). To correlate the building damage due to a specific tornado intensity, several proposals could be found in literature. The so-called Fujita scale or *F*-scale damage rating to measure tornado intensity was introduced by Fujita in 1971: according to this procedure, tornados are rated from low to high as light damage (F-0), moderate damage (F-1), considerable damage (F-2), severe damage (F-3), devastating damage (F-4), incredible damage (F-5), and inconceivable damage (F-6 or above) (Dakshina et al. 2008). Table 2 describes the type of damage and Fujita's estimate of wind speed for each *F*-scale rating Fujita (1971). This scale, widely used to analyze the intensity of tornadoes by the US National Weather

Table 1 Tornado events in the northeast of Italy, 1900–2017

	Municipality	Day	Month	Year	Region	*F*-scale
1	Venezia	11	9	1970	Veneto	F4
2	Enego	24	7	1983	Veneto	F2
3	Bibione	21	7	1997	Veneto	F2
4	Cerea-Legnago	18	6	2003	Veneto	F0
5	Gaianigo	5	7	2004	Veneto	F0
6	Vicenza-Bertesina	20	8	2004	Veneto	F1
7	Montecchio Precalcino	13	8	2004	Veneto	F2
8	Caorle	21	8	2004	Veneto	F1
9	Asolo	29	6	2006	Veneto	F1
10	Venezia	28	7	2006	Veneto	F1
11	Pontelongo	28	7	2006	Veneto	F1
12	Mogliano	28	7	2006	Veneto	F1
13	Portogruaro	5	5	2007	Veneto	F0
14	Farra d'Alpago	9	7	2007	Veneto	F2
15	Padova	6	7	2008	Veneto	F1
16	Zermeghedo	19	3	2009	Veneto	F1
17	Bovolenta	29	4	2009	Veneto	F0
18	Candiana	29	4	2009	Veneto	F0
19	Riese Pio X	6	6	2009	Veneto	F3
20	Madonna di Lourdes	29	8	2009	Veneto	F0
21	Merlara	29	8	2009	Veneto	F1
22	Fosso‘	19	6	2010	Veneto	F2
23	Porto Secco-Pellestrina	23	7	2010	Veneto	F2
24	Montecchio Maggiore	8	11	2010	Veneto	F1
25	Cerro Veronese	27	5	2011	Veneto	F1
26	Venezia-Treporti-Cavallino-Torre di Fine	12	6	2012	Veneto	F1
27	Brugine	27	4	2013	Veneto	F0
28	Mirabella	25	5	2013	Veneto	F0
29	Villorba	23	3	2014	Veneto	F0
30	Maserada sul Piave	23	3	2014	Veneto	F1
31	Canda	27	4	2014	Veneto	F0
32	Cavarzere	23	5	2014	Veneto	F0
33	Sant' Appollinare Veneto	12	7	2014	Veneto	F1
34	Caposile	23	8	2014	Veneto	F1
35	Melara	13	10	2014	Veneto	F3
36	Mira	8	7	2015	Veneto	F4
37	San Giorgio in Bosco	21	7	1895	Veneto	F1
38	Isola di Burano	23	7	1932	Veneto	F2
39	Porto Levante	4	10	1893	Veneto	F2
40	Porto Viro	16	7	1933	Veneto	F0
41	Padova	10	7	1939	Veneto	F1
42	Vicenza	9	8	1948	Veneto	F1
43	Adria	22	8	1953	Veneto	F3

Table 1 continued

	Municipality	Day	Month	Year	Region	*F*-scale
44	Lignano Sabbiadoro	19	7	1981	Veneto	F0
45	Polesella	19	7	1892	Veneto	F2
46	Boara Polesine	8	6	1990	Veneto	F2
47	Ramodipalo	24	6	1993	Veneto	F2
48	Cadoneghe	7	7	2001	Veneto	F2
49	Ormelle	25	7	2006	Veneto	F1
50	Quinto-Morgano	14	9	2015	Veneto	F1
51	Montello	24	7	1930	Veneto	F5
52	Pasian Schiavonesco	25	7	1884	Friuli Venezia Giulia	F1
53	Duino	21	9	1964	Friuli Venezia Giulia	F1
54	Trieste	1	9	1994	Friuli Venezia Giulia	F0
55	Capriva del Friuli	27	8	1971	Friuli Venezia Giulia	F2
56	Palmanova-Castions di Strada	27	8	1971	Friuli Venezia Giulia	F1
57	San Quirino	4	6	1999	Friuli Venezia Giulia	F2
58	Fagagna	26	3	2001	Friuli Venezia Giulia	F0
59	Sgonico	21	8	2014	Friuli Venezia Giulia	F1
60	Carlino	4	4	1979	Friuli Venezia Giulia	F1
61	Ronchi dei Legionari	31	8	1980	Friuli Venezia Giulia	F1
62	Aiello del Friuli	19	7	1981	Friuli Venezia Giulia	F2
63	Bannia	21	8	1988	Friuli Venezia Giulia	F2
64	Brugnera	4	8	2001	Friuli Venezia Giulia	F0
65	Prata di Pordenone	5	8	2001	Friuli Venezia Giulia	F1
66	Ragogna	5	8	2001	Friuli Venezia Giulia	F1
67	Sacile	9	8	2001	Friuli Venezia Giulia	F2
68	Pasiano	10	8	2001	Friuli Venezia Giulia	F0
69	San Leonardo	28	8	2003	Friuli Venezia Giulia	F1
70	Gemona	29	8	2003	Friuli Venezia Giulia	F1
71	Strassoldo	26	8	2004	Friuli Venezia Giulia	F1
72	Gorizia	25	7	2006	Friuli Venezia Giulia	F1
73	Rigolato	26	7	2006	Friuli Venezia Giulia	F1
74	Cassacco	9	12	2006	Friuli Venezia Giulia	F2
75	Sarone di Caneva	9	12	2006	Friuli Venezia Giulia	F1
76	S. Michele in Tagliamento- Manzano	26	5	2007	Friuli Venezia Giulia	F1
77	Cornadella	20	7	2008	Friuli Venezia Giulia	F0
78	Orcenico Superiore	6	6	2009	Friuli Venezia Giulia	F2
79	Dignano	11	5	2014	Friuli Venezia Giulia	F0
80	Bagnaria Arsa	27	5	2014	Friuli Venezia Giulia	F1
81	Aviano	27	4	2015	Friuli Venezia Giulia	F0
82	Majano	4	8	1979	Friuli Venezia Giulia	F1

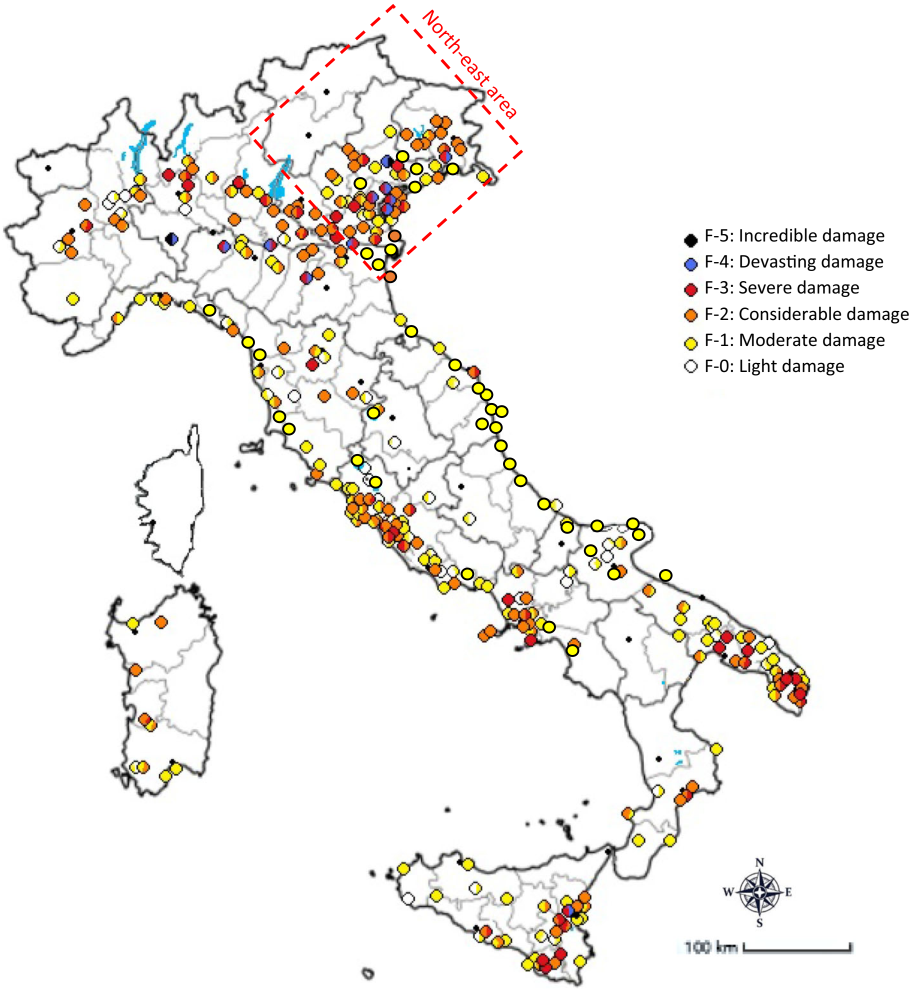


Fig. 3 Catalogue of tornado from 1905 to 2017 in Italy (only events with intensity information)

Service, is of main interest, as up to 1950 tornadoes have been assigned *F*-scale ratings based on historical accounts of the damage (Dakshina et al. 2008). In order to compare the damage assessment introduced by the *F*-scale rating with wind speed, the relationship among the Beaufort force—used for estimating wind speeds through hurricane intensity—with the Mach number—describing the near-sonic speed—and with the Fujita (1971, 1981) and Fujita and Pearson (1973) is reported in Fig. 9. In this figure, F1 corresponds to the twelfth level of the Beaufort scale, and F12 corresponds to Mach number 1.0. F0 was placed at a position specifying no damage (approximately the eighth level of the Beaufort scale), in analogy to how the Beaufort's zeroth level specifies little to no wind. From these wind speed numbers, qualitative descriptions of damage were made for each category of the Fujita scale, and then these descriptions were used to classify tornadoes. The official Fujita scale category is determined by specialists by means of aerial or ground analysis, and with the support of other documents based on ground-swirl patterns (cycloidal marks),

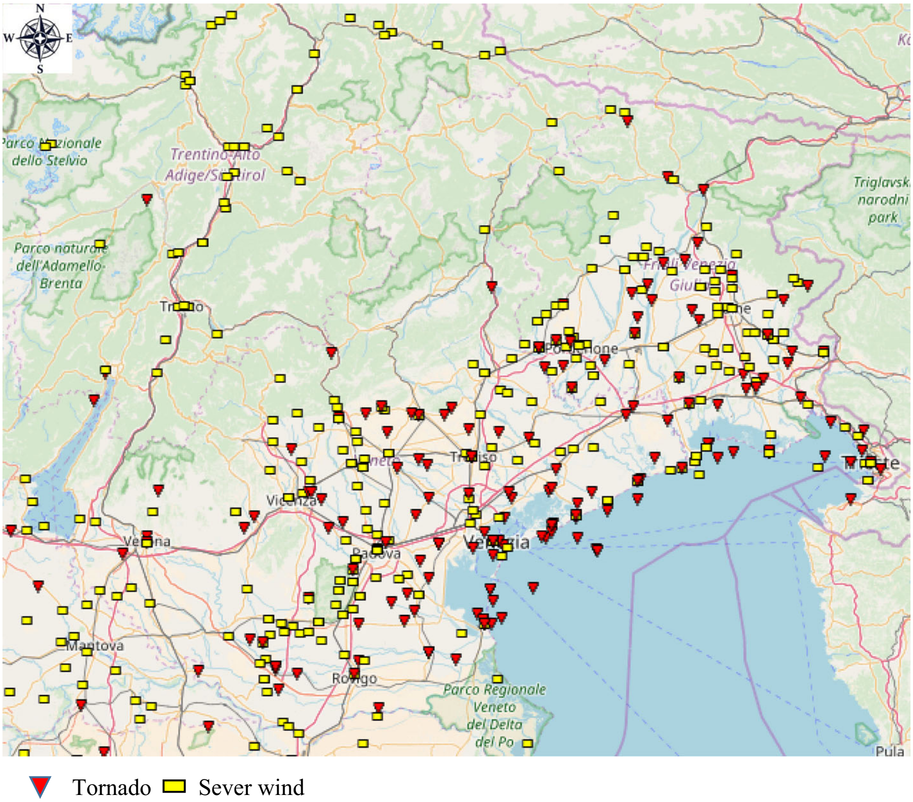
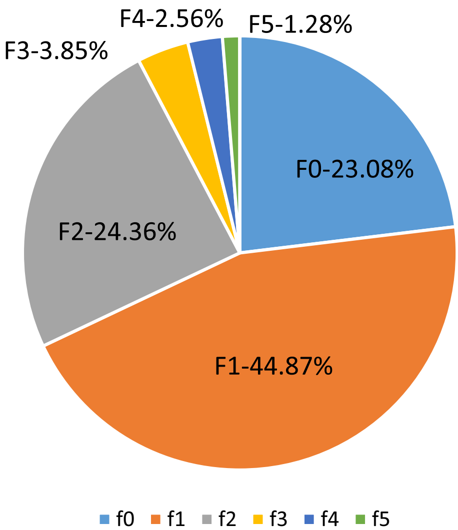


Fig. 4 Catalogue of tornado and severe wind from 1905 to 2017 in the northeast of Italy (ESWD Catalogue, Dotzek et al. 2009)

Fig. 5 The intensity of tornadoes occurred in northeast Italy and evaluated according to the *F*-scale



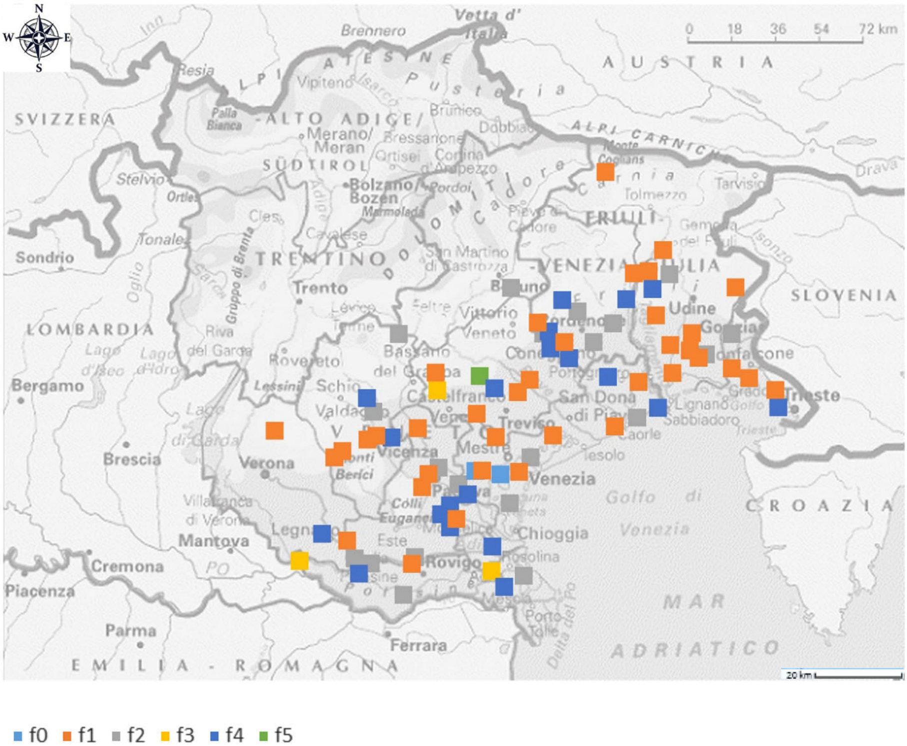


Fig. 6 Tornadoes occurred in northeast Italy: spatial distribution (1884–2017)

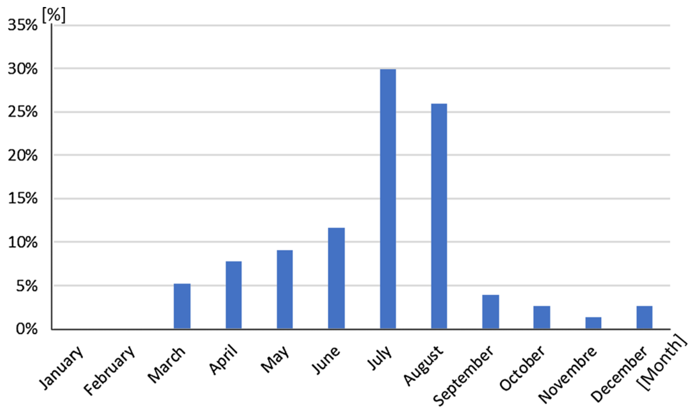


Fig. 7 Tornadoes occurred in northeast Italy: time-season distribution (1884–2017)

reports and damage photographs, radar tracking, testimonies, photogrammetry or videogrammetry, motion picture records. The Fujita scale is consequently a subjective method, as it is based onto visual interpretation of wind damage ranging from F0 to F5 based on the increasing severity of damage, primarily to a "well-constructed" or "strong" wooden-framed house (Fujita 1971; Fujita and Pearson 1973; Abbey 1976; Edwards et al.

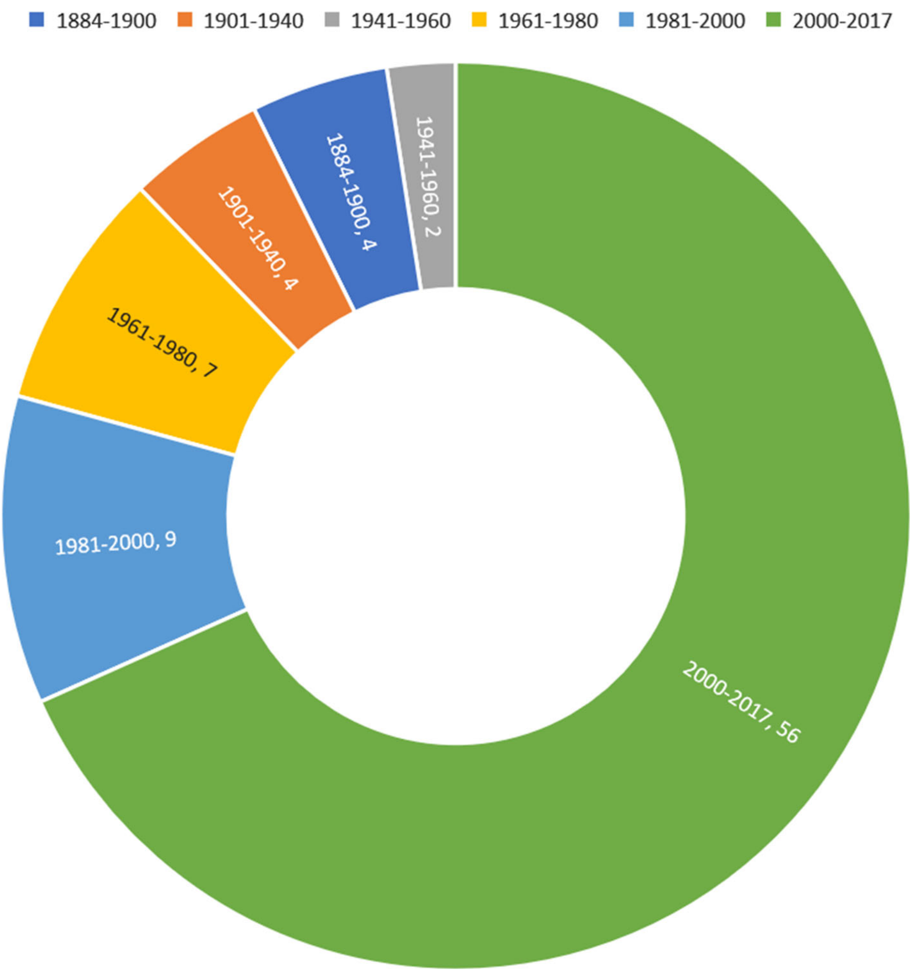


Fig. 8 Tornadoes occurred in northeast Italy: time-year distribution (1884–2017)

2013). As Grazulis (1993) noted, the single-paragraph descriptions of damage given by Fujita are vague and limited in scope. Fujita (1992) itself realized residences were not constructed homogeneously worldwide, and he devised corrections to compensate for those differences in assigning *F*-scale numbers. Possible misclassifications were confirmed by Phan and Simiu (1999), evidencing how damage observed after the F5 Jarrell tornado (Texas 1997) could have been produced by wind speeds lower than those characterizing a F5 event (117–142 m/s) determining that wind speeds of longer duration resulted in greater damage to residences. Other doubts arise from the construction quality: if a barn or manufactured home is destroyed, the tornado may be assigned a more intense Fujita scale rating if it passes over a well-constructed building and causes little or no damage (McDonald 2001). Another limitation deals with the localization and the path of the tornado: over open country, the classification of damage could be rated at a lower category, because there are no or less evidences of damages (McDonald 2001). To improve tornadoes classification some procedures and estimation methods were developed over the years

Table 2 Fujita scale (1971)

F-scale	Damage intensity	Wind speed (km/h)	Type of damages
F-0	Light damage	64–116	Some damage to chimneys and TV antennae; breaks twigs off trees; pushes over shallow-rooted trees
F-1	Moderate damage	117–180	Peels surface off roofs: windows broken; light trailer houses pushed or overturned; some trees uprooted or snapped; moving automobiles pushed off the road. 73 mph is the beginning of hurricane wind speed
F-2	Considerable damage	181–253	Roofs torn off frame houses leaving strong upright walls; weak buildings in rural areas demolished; trailer houses destroyed; large trees snapped or uprooted; railroad boxcars pushed over; light object missiles generated; cars blown off highway
F-3	Severe damage	254–332	Roofs and some walls torn off frame houses; some rural buildings completely demolished; trains overturned; steel-framed hangar-warehouse type structures torn; cars lifted off the ground; most trees in a forest uprooted; snapped, or leveled
F-4	Devastating damage	333–419	Whole frame houses leveled, leaving piles of debris; steel structures badly damaged; trees debarked by small flying debris; cars and trains thrown some distances or rolled considerable distances; large missiles generated
F-5	Incredible damage	420–512	Whole frame houses tossed off foundations; steel-reinforced concrete structures badly damaged; automobile-sized missiles generated; incredible phenomena can occur
F-6 or above	Inconceivable damage	512–Sonic	Speed should a tornado with the maximum wind speed in excess of F6 occur, the extent and types of damage may not be conceived. A number of missiles such as ice boxes, water heaters, storage tanks, automobiles will create serious secondary damage on structures

because the FS was found to be not so accurate in order to estimate the tornado intensity (e.g., Schaefer and Galway 1982; Doswell and Burgess 1988; Wurman et al. 2007, 2008; Doswell et al. 2009; Edwards et al. 2013; Ashley et al. 2014). Consequently, a new scale was developed, the so-called Enhanced Fujita scale (EF), which was associated with the damage observation (Tables 3, 4). Figure 10 shows this new scale reporting the conversion factor from the damage *F*-scale to the original wind speed *F*-scale for each building type. A comprehensive 28 Damage Indicators (DIs) and Degrees of Damage (DoD) are included to describe with a more sophisticated procedure the tornado event. Consequently, a rate from EF0 to EF5 could be assigned. Further innovation of the last decades includes advanced and more precise instruments and technologies able to concur to a precise observational survey: e.g., the geographic information science (GIScience) often used in combination with global positioning systems (GPSs), mobile Doppler radar (MDR), together with georeferencing–digitizing of the local weather services procedures are at the base of the possibility to digitalize completely one single event (Marshall et al. 2008a, b, 2012a, b; Prevatt et al. 2012; Roueche and Prevatt 2013; Wurman and Alexander 2005; Wurman et al. 2007; Alexander and Wurman 2008). These technologies help in reducing at the minimum level potential errors during post-event surveys (Wurman et al. 2007; Edwards et al. 2013). And even if no more than 150 tornadoes in the last two decades have been observed by MDR, this will be probably the future of the tornado damage intensity

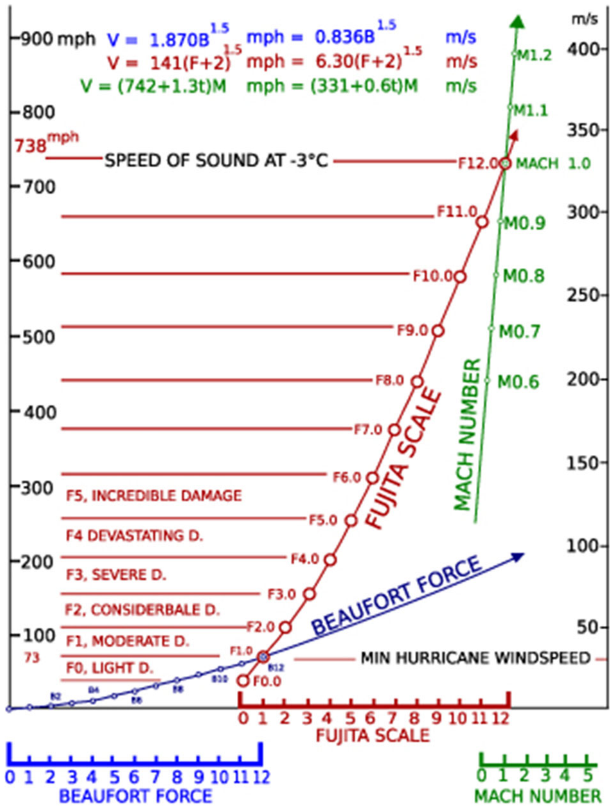


Fig. 9 Relationship among Beaufort force, Fujita scale and Mach number

Table 3 Damage indicators (DIs) for the enhanced Fujita scale

Small barns/farm buildings (SBO)	One- or two-family residences (F12)
Single-wide mobile home (MHSW)	Double-wide mobile home (MHDW)
Apt/Condo/Twnhse < 3 stories (ACT)	Motel (M)
Masonry Apt or motel (MAM)	Small retail Bldg—fast food (SRB)
Small professional Bldg (SPB)	Strip mall (SM)
Large shopping mall (LSM)	Large isolated retail Bldg (LIRB)
Automobile showroom (ASR)	Automotive service Bldg (ASB)
School—1 story elementary (ES)	School—Jr or Sr High (JHSH)
Low-rise (1–4 story) Bldg (LRB)	Mid-rise (5–20 story) Bldg (MRB)
High-rise (> 20 story) Bldg (HRB)	Institutional Bldg (IB)
Metal Bldg system (MBS)	Service station canopy (SSC)
Warehouse Bldg (WHB)	Transmission line tower (TLT)
Free-standing tower (FST)	Free-standing pool (FSP)
Tree-hardwood (TH)	Tree-softwood (TS)

Table 4 Damage indicators (DIs) for the enhanced Fujita scale

Damage state (*DS*)	Description
DS A	Slight damage to roofs and minor structures (antennas, tents, car-cover)
DS B	Roof extended damage (complete peel), frame structure with no damages
DS C	Total removal of the roof, frame structure with no damages
DS D	Damage extended to the last upper quarter of the walls
DS E	Damage extended to all floors
DS F	Whole structure leveled

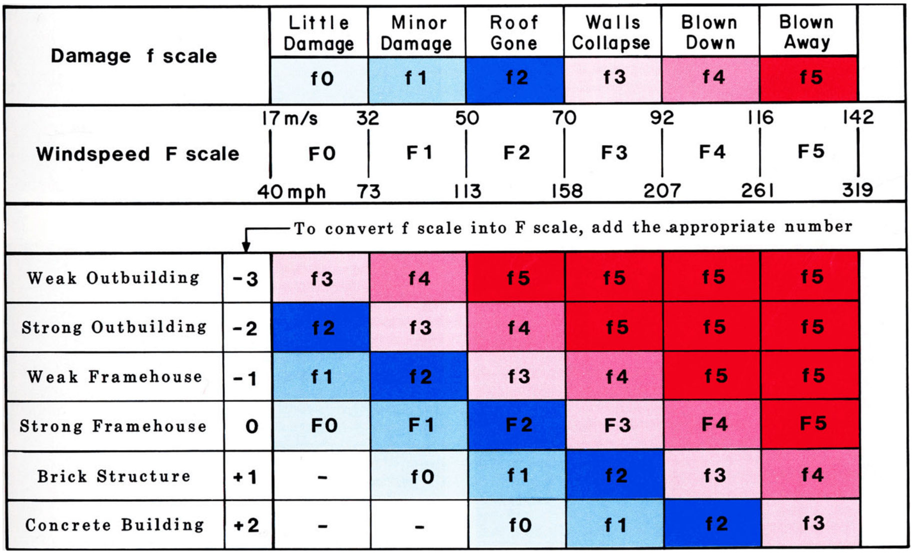


Fig. 10 Damage *F*-scale proposed by Fujita (1992)

estimation, (Wurman and Alexander 2005; Edwards et al. 2013; Snyder and Bluestein 2014). A final clarification should be also introduced: although a direct comparison between USA, European and specifically, Italian events is difficult to be made, given the different construction practices between the central USA and Europe, it is possible that the intensity of European tornadoes is underestimated; a discussion about this issue can be found in Antonescu et al. (2018).

5 Damage assessment of the most extreme tornado event recorded in the northeast of Italy

In this section, the damage assessment of the most extreme tornado event recorded in the northeast of Italy ranging from F3 to F5, Fujita scale are reported. A damage scale has been defined accordingly to Fujita scale (1971): Table 4 lists the damage states (DSs) adopted, including six damage levels, from DSA (slight damage) to DSF (the highest damage level corresponding to the whole structure leveled). The analyzed events are identified in Fig. 11. To compare these different events effects on buildings, historical documents, meteorological data, in situ surveys or literature data were analyzed. A summary of the most relevant data of all these historical tornadoes data is reported in Table 5.

5.1 Riese Pio X event, F3 (June 6, 2009)

This tornado caused great damage to the village of Vallà of Riese Pio X, in the province of Treviso. The destructive path of the tornado is reported in Fig. 12a, together with the building damage map according to the adopted DS classification and the associated Gaussian probability density function (a geostatistical procedure that generates an estimated surface from a scattered set of damage points with DS-damage values). In Fig. 12b, the radar image of the storm is depicted. The recorded path was nearly 13 km, with 2 km as maximum width. However, a more extended area was hidden by this event (112 km). In this case, the tornado damage was not so extended, but particularly concentrated in a zone (the Vallà city): the majority of the analyzed buildings (64.36%) were subject to moderate damage (DSA–DSB), whereas 12.8% to slight damage (DSC–DSD) and 8.9% suffered by extensive damage or structural collapse (DSE–DSF) (Fig. 12c, d). No victim and thirty injuries were reported. The most damages reported were: roof discover, electric plant and public illumination out of use, instability of buildings under construction, light structure leveled, old masonry building partially demolished, large devastation of agricultural cultivation, etc. The documents used to derive this damage survey are: ARPAV (2009),

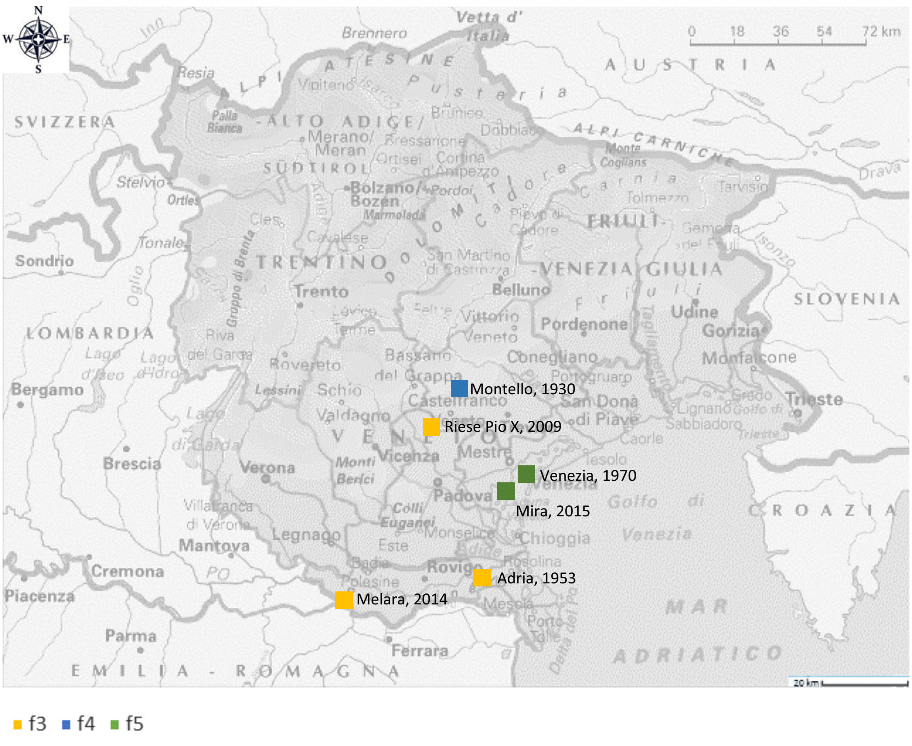


Fig. 11 Most extreme tornado event recorded in the northeast of Italy (1900–2017)

Table 5 Relevant data for the northeast Italian tornadoes analyzed

Place	Year	Fujita scale	DSA–DSB (%)	DSC–DSD (%)	DSE–DSF (%)	Path length	Path width	Injured	Death	Actualized damage building estimates	Reported maximum wind speed (km/h)
Riese Pio X	2009	F3	64.36	12.80	22.84	13.00	2	30	0	12,000,000.00	270–320
Adria	1953	F3	0.00	83.33	16.67	13.00	n.a.	n.a.	n.a.	1,620,000.00	250–270
Melara	2014	F3	66.10	19.60	14.30	9.50	n.a.	4	0	1,500,000.00	250–270
Venezia	1970	F4	72.59	0.66	26.75	65.00	n.a.	500	36	54,740,000.00	340–350
Mira	2015	F4	76.70	14.40	8.90	10.00	1.1	84	1	70,000,000.00	340–350
Montello	1930	F5	58.07	21.56	20.37	80.00	0.3–0.09	100	23	n.a.	420–460

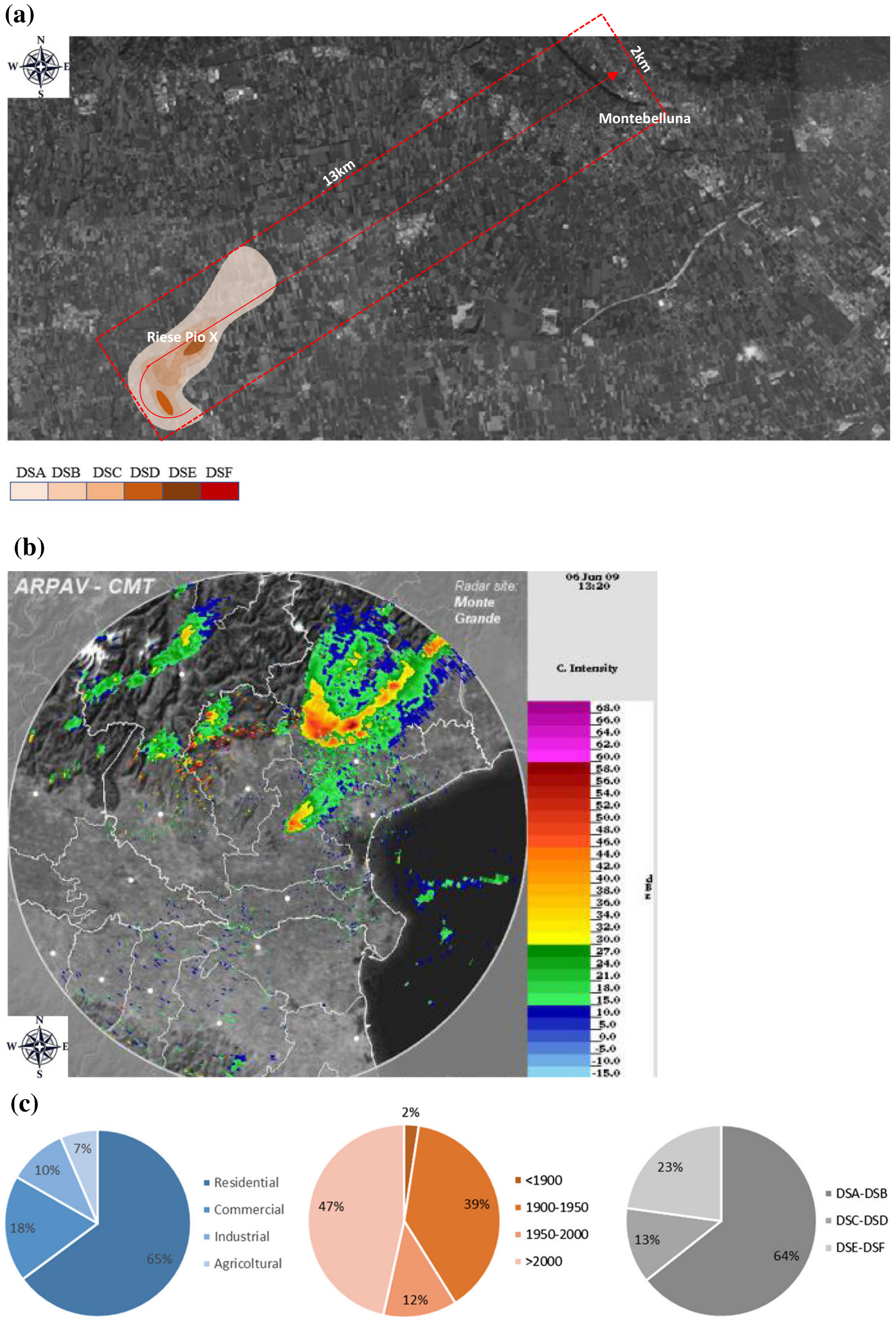


Fig. 12 Riese Pio X event, F3 (June 6, 2009): **a** the reconstruction of the tornado pathway, with a colourmap Gaussian interpolation of the expected most damaged zone; **b** the radar image of the storm (ARPAV 2015); **c** building use, construction year and damage category; **d** DSF areas, main damages

Fig. 12 continued

Archive of the Riese Pio X Municipality (2010), Barbi et al. (2009) Tormena (2009), photograph archive of the author.

5.2 Adria event, F3 (August 24, 1953)

Historical newspapers reported that a violent tornado fell between Valliera, Retratto (Adria) and Loreo, (13 km path length). The destructive path of the tornado is reported in Fig. 13a. Most of the damages (83.33%) analyzed buildings were subject to slight damage (DSC), 10.42% suffered by extensive damage DSE, and structural collapse in 6.25% (DSF) (Fig. 13b). The most damages reported were: roof extended damage (complete peel) and total removal of the roof especially for farm structures in isolated position outside the inhabited areas. Large damage has been reported also for cultivation in the nearest of the tornado path. The documents used to derive this damage survey are: Abinanti et al. (2015), Historical Archive of the Adria Municipality (2017) and Gazzettino (2017).

5.3 Melara event, F3 (October 13, 2014)

A violent tornado hidden the city of Melara in October 2014, characterized by temperatures far above the average (according to ARPAV 2017: $T_{m,October}$ = 14 °C; $T_{m,November}$ = 12.2 °C), the mildest since 1925 to this part (ARPAV 2017). The tornado path was not so extended; however, a wide amount of damages was reported in a very large zone of the low plain of Veneto, between Rovigo and Padova province. Three injuries were reported. Other cities were hidden with minor damages (Lendinara, Stienta, Occhiobello, Este), far from the

(a)

(b)

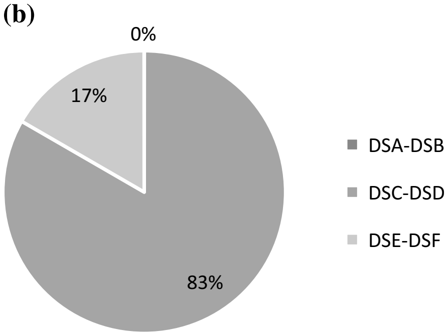


Fig. 13 Adria event, F3 (August 24, 1953): **a** the reconstruction of the tornado pathway; **b** building damage estimated category

tornado paths, probably involved in a very large wind-storm event. The path simulation of the tornado according to the damage reported is depicted in Fig. 14a. The tornado path was characterized by a length of about 9.5 km, with localized damages in the San Francesco di Melara city: no damages were reported in the nearest as a wide countryside is all around, without buildings. Most of the analyzed buildings (66.1%) were subject to moderate damage (DSA–DSB), whereas 19.60% to slight damage (DSC–DSD) and only 14.30% suffered by extensive damage or structural collapse (DSE–DSF) (Fig. 14b). The most damages reported were: slight damage to roofs and minor structures (agricultural small and light structures) and roof extended damage (partial or complete peel). Minor construction also has been hidden by the event, inducing rotations of small wall and distortion of high and slender steel structures. The documents used to derive this damage survey are: ARPAV (2014) and Gazzettino (2017), photograph archive of the author.

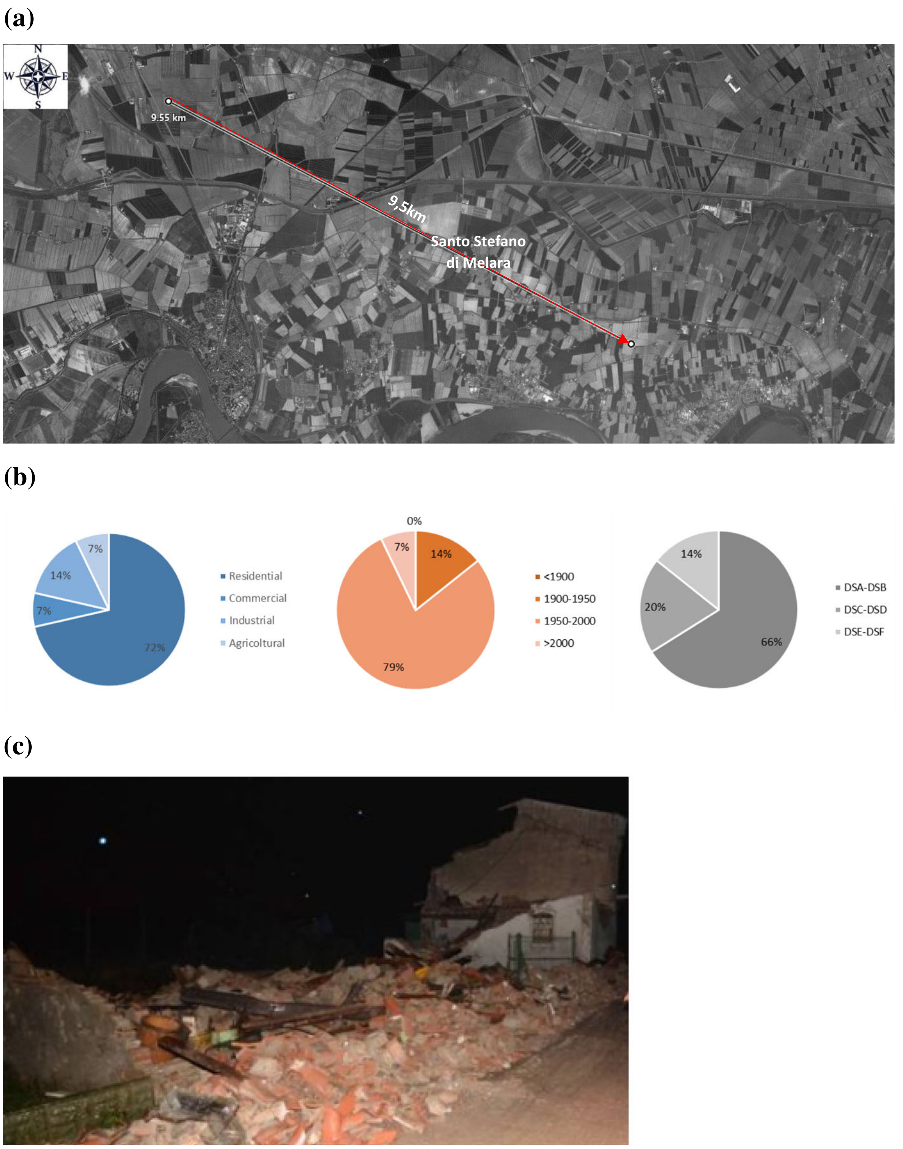


Fig. 14 Melara event, F3 (October 13, 2014): **a** the path of the tornado; **b** building use, construction year and damage category; **c** DSF areas, main damages

5.4 Venezia event, F4 (September 11, 1970)

Unstable atmospheric condition, high temperature coming from the north African regions, a large low pressure area on the north of Italy, with two minimum points on the Pianura Padana (one around Milan and one around Venice) and one large area of high pressure on the east Alps were the premises of an extraordinary event of "severe weather," where the transit of a violent supercell storm occurred associated with one of the most intense tornadoes ever observed, not only in the area but on the entire Italian peninsula, with the highest number of death (36) and injured people (500). A very long path—65 km—characterized this tornado (Fig. 15a): starting in the nearest of the Euganean hill (Teolo),

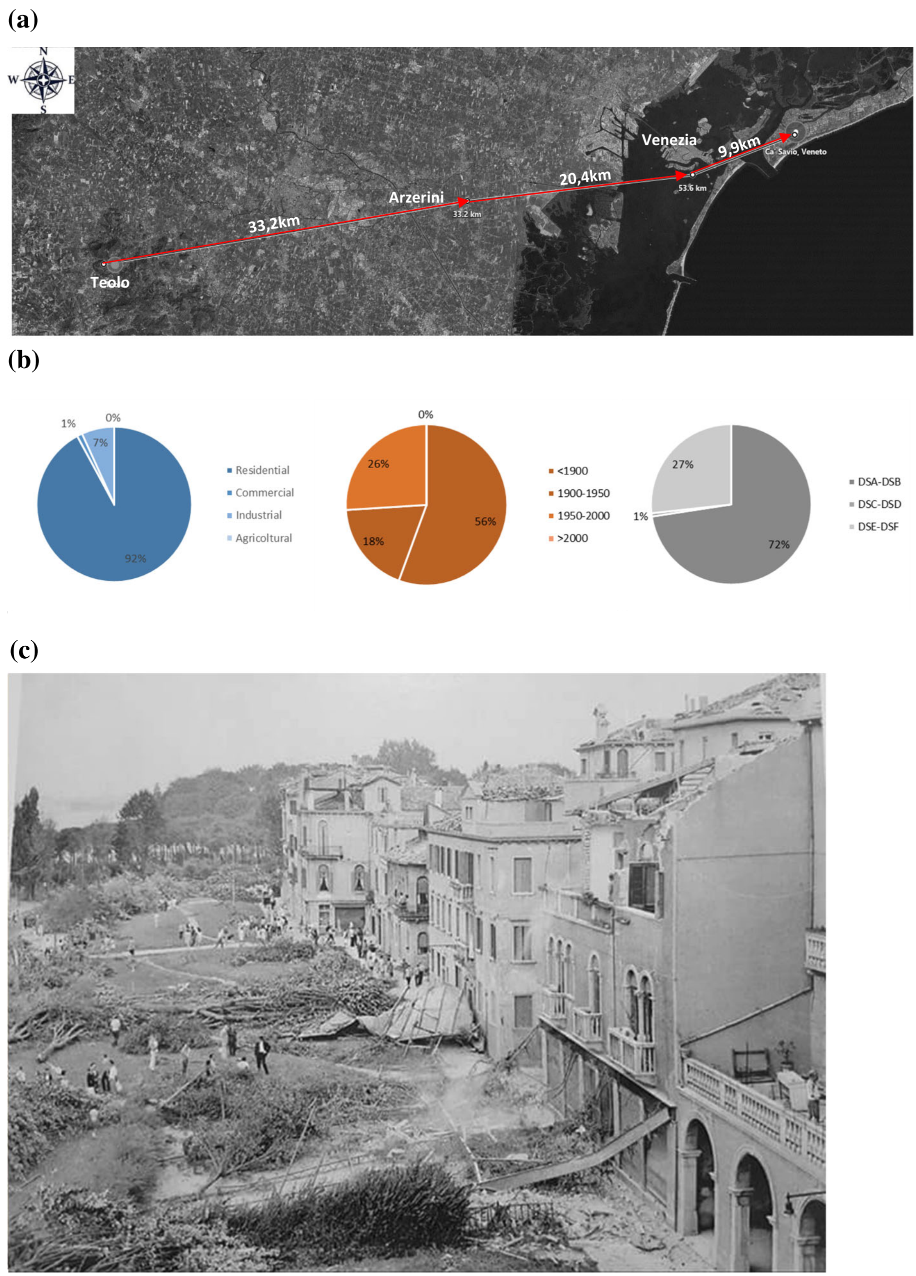


Fig. 15 Venezia event, F4 (September 11, 1970): **a** the path of the tornado; **b** building use, construction year and damage category; **c** DSF areas, main damages

Fig. 15 continued

the path touched Padova, Albignasego, Ponte San Nicolò, Abano, Selvazzano, Campoverardo di Camponogara, San Bruson di dolo, Giare, Dogaletto, Fusina, then prosecuted in the Venice lagoon devasting the Grazie Island and the Lido island, leaving damages also in the city of Venice, and then Saint Elena Island, terminating at Cà Savio. The majority of the damages (72.59%) buildings were subject to moderate damage (DSA–DSB), 0.66% suffered by slight damage DSC-DSD, and extensive damages in 26.75% (DSE–DSF) (Fig. 15b, c). The most damages reported were: roof extended damage (partial in the nearest of the path, complete peel for building along the path wherever the complete collapse was not induced); the Fusina camping was completely destroyed; the electrical plants and devices, including the public illumination, were completely destroyed; the Grazie Island hospital was completely destroyed; a large ship (the ANCIL) was completely lifted up and sinked with the complete crew (21 persons); then returning into the landside, the tornado completed demolished the naval academy "Morosini," the "Penzo" stadium, the "Nicelli" airport, the Ca Savio camping. The documents used to derive this damage survey are: Abinanti et al. (2015), State Archive of Venice (2017) and Gazzettino (2017).

5.5 Mira event, F4 (July 8, 2015)

A very similar event of the Venezia event in 1970 was recorded in 2015. One victim and 84 injuries were reported. The most hidden cities were Pianiga, Mira and Dolo. The destructive path of the tornado is reported in Fig. 16a, together with the building damage map according to the adopted DS classification and the associated Gaussian probability density function. In Fig. 16b, the radar image of the storm are depicted. The path length was approximatively of 10 km, with a maximum width of 1.1 km. The majority of the

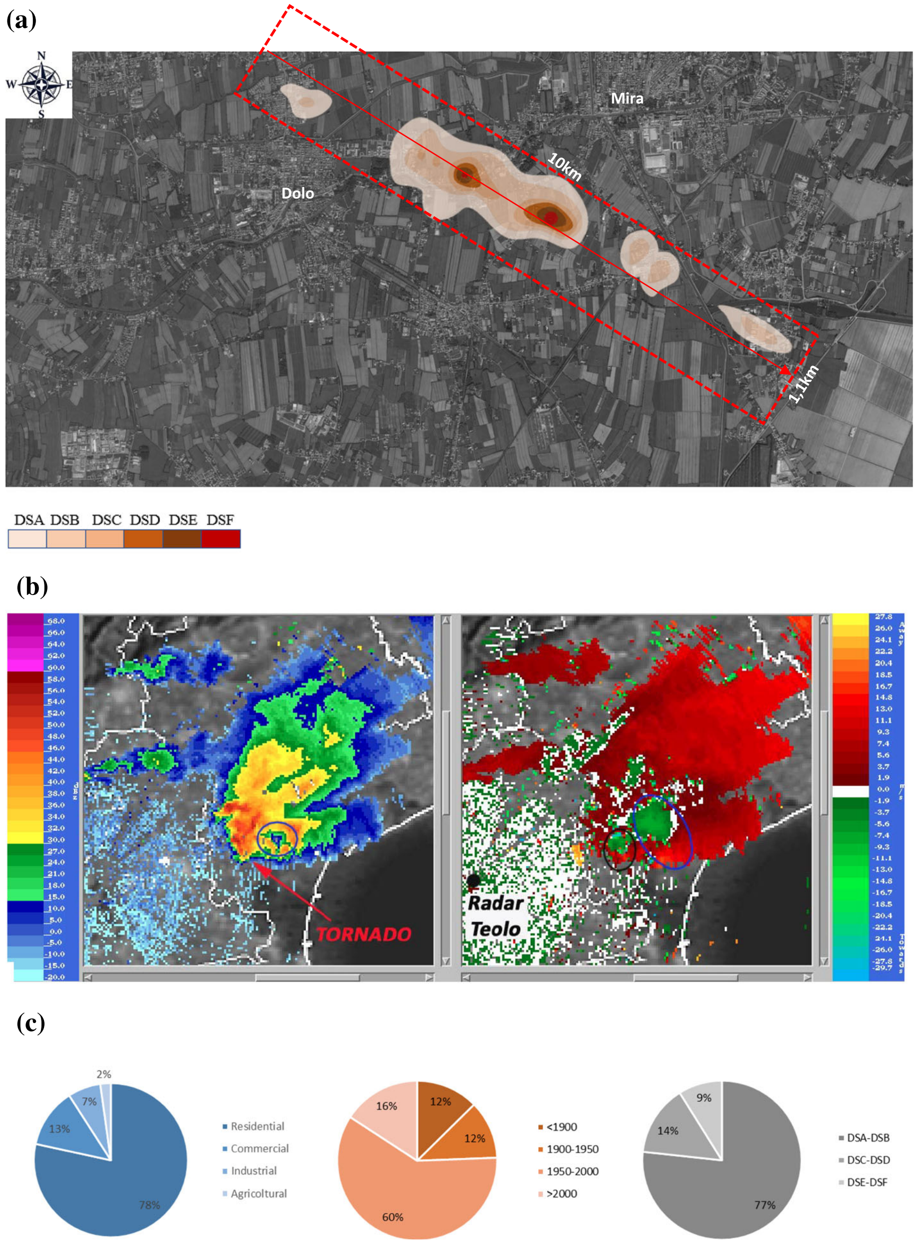


Fig. 16 Mira event, F4 (July 8, 2015): **a** the path of the tornado with a colourmap Gaussian interpolation of the most damaged zone; **b** the radar image of the storm: reflectivity PPI at 2.5° on left, radial speed at 2.5° on the right (ARPAV 2015); **c** building use, construction year and damage category; **d** DSF areas, main damages

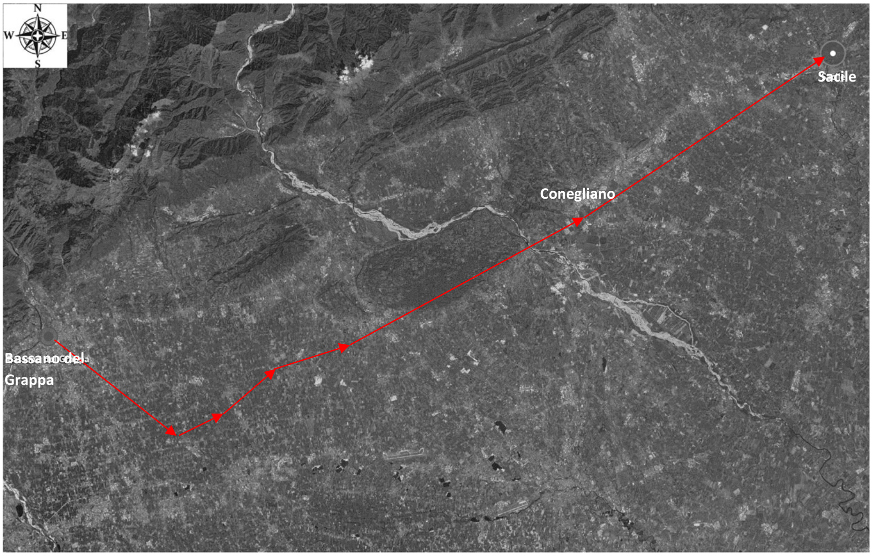
Fig. 16 continued

analyzed buildings (76.7%) were subject to slight damage (DSA–DSB), whereas 14.4% to moderate damage (DSC–DSD) and only 8.9% suffered by extensive damage or structural collapse (DSE–DSF) (Fig. 16c, d). The most damages reported were: the complete destruction of historical buildings and rural villas, large roof discovering including masonry walls elevation on the upper part of the buildings, cars and light structure lifted up, complete destruction of public electrical towers and antennas, tree devastation. The documents used to derive this damage survey are: Abinanti et al. (2015) and Gazzettino (2017), photograph archive of the author.

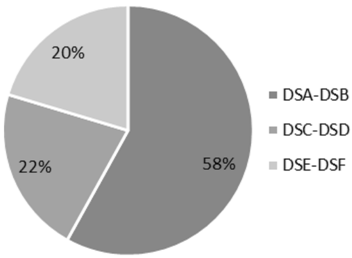
5.6 Montello event, F5 (July 24, 1930)

On July 24, 1930, the city of Montello in the northeast of Italy, in the southern of the Alps, was hit by the strongest tornado in Europe on record. The tornado was rated as F5, destroying whatever was in the path (e.g., large masonry buildings like churches). The Montello tornado persisted for 1.5 h and produced a damage track 80 km long, roughly between Treviso and Pordenone, causing 23 fatalities (Fig. 17a). The long damage track and persistence of the tornado suggest that this event may have been caused by several tornadoes produced by the same cyclic supercell. The tornado originated in the nearest of Bassano del Grappa, passing by Castello di Godego, Vallà di Riese, Caselle di Altivole, Sant'Andrea di Montebelluna, Sant'Eurosia di Volpago, Nervesa, Susegana, Conegliano, Sacile, ending around the Cellina river near Pordenone. Everything in the path was destroyed: the main buildings (58.07%) were subject to moderate damage (DSA–DSB), 21.56% suffered by slight damage DSC-DSD, and extensive damages in 20.37% (DSE–DSF) (Fig. 17b, c). The most damages reported were: the complete destruction of houses, the collapse of the Selva church demolishing the complete longitudinal walls and the roof,

(a)



(b)



(c)

Fig. 17 Montello event, F5 (July 24, 1930): **a** the path of the tornado; **b** building damage estimated category; **c** DSF areas, main damages

house's roof was peeled completely in the nearest of the tornado path, and agricultural cultivation was devasted; moreover, missiles (mostly flying roof, or masonry and wood-beam coming from the devastation of were observed. Along a width of 300–900 m (depending on the tornado position) all was devasted and lifted also for kilometers of distance. The documents used to derive this damage survey are: Abinanti et al. (2015), Zanardo (2015) and Gazzettino (2017).

6 Structural codes

New buildings are every day designed and built ignoring a precise and well-known cause of deficiency. When an extreme wind event occur, negative and positive pressure on building walls could increase until partial or global uplift of entire structures are reached. Some other circumstances (like increasing internal pressure due to window breaking; or heavy materials flying onto the structure) are moreover never analyzed in building codes. Due to these unexpected loads, while heavier construction should be safe (e.g., reinforced concrete structures), lighter construction is often damaged permanently (e.g., wooden roof structures, secondary substructures as external garages, gravel, insulation, shingles, roofing membranes, and brick veneer). Not only the weight, but also the shape of structure could influence the possibility to survive to extreme events: e.g., "catching structures" like sails or derived form, are prone to collapse soon, and to be transformed into bullet against nearside constructions. As a matter of fact, the most repeatable dynamic effects on existing structure due to extreme events are (a) suction phenomena (horizontal loads with respect to the ordinary gravity loads onto building components) and (b) wind uplift/down lift (additional dynamic pressures with respect to the vertical lift). The immediate consequence relates to damages to the roof nailed connection. The degeneration of these damages, also incremented by missile damages, is the loss of the structural integrity of the whole construction, due to the increasing internal pressure. The wind exercises on the constructions actions that vary in time and in the space causing, in general, dynamic effects. However, for the usual calculation procedure, actions are conventionally calculated with equivalent static forces. This calculation procedure does not apply:

(a) for the constructions of unusual shape or type,
(b) or of great height or length,
(c) or of significant slenderness and lightness,
(d) or of remarkable flexibility and reduced dissipative capacity,
(e) extreme wind events ($v > 30$ m/s)

In these cases, the wind produces effects whose evaluation requires the use of methodologies calculation and experiments adequate to the state of the art; and the static approach is no more useful to be applied, because the interaction of the wind with the structure can give rise to aeroelastic actions, whose effects modify the own frequencies and/or the damping of the structure causing instability phenomena, among which the galloping, the torsional divergence, the flutter, the partial or global uplift, etc. As a fact, while actual design procedures provide a sufficient capacity to resist against low consequence tornadic events (EF0–EF2), for higher wind speed no specific loads and verifications are provided in codes and standard. The EN Eurocodes are a series of ten European Standards, from EN 1990 to EN 1999, providing a common approach for the structural design of buildings. Extreme wind events ($v > 30$ m/s) are not covered in Eurocode

EN1991-4 (2005), which deals with "Actions on structures," and in particular with "Part 1–4: General actions—Wind actions": this is a strong deficiency, considering that other extreme loads verification is included in Eurocodes, e.g., Eurocode EN 1998 (2005) is entirely dedicated to the "Design of structures for earthquake resistance," providing accurate verification procedures and incrementing the safety and security of a wide amount of new and existent building. Specific Guidelines exists in US, but only for special buildings like storm shelters (ICC 500, 2014). For common buildings no specific guidelines are given (ASCE 2013). Recently, new standards have been published for special buildings (e.g., storm shelter) providing safe buildings for areas of the country where powerful twisters with winds up to 250 mph are most likely to occur (northern and northwest portions of Texas and the northern half of Louisiana). However, a large gap remains for residential buildings, which are the largest category of buildings more prone to tornado damages. The time has gone to traduce scientific findings and the engineering experience into new codes and standards, to protect citizens against extreme wind events, providing at the same time safer and life-longer building.

7 Ongoing research

Figure 18 schematically shows the interaction between the airflow and a generic building profile, highlighting that the direction and pressure intensity mainly depend on the inclination of the roof pitches (Tominaga et al. 2015). Various types of tornado simulators have been built in the past to create tornado-like vortices in the laboratory and study the vortex dynamics by varying the controlling parameters (Ward 1972; Snow and Lund 1988; Monji and Wang 1989; Church et al. 1979; Haan et al. 2008; Matsui and Tamura 2009; Hashemi-Tari et al. 2010). However, although the increasing experience on tornado simulations, limited attempts have been made to quantify tornado-induced loading. Case et al. (2014) investigated the effect of different building geometry on the forces and pressures that low-rise buildings would experience in a simulated tornado with a swirl ratio comparable to what has been measured and recorded for full-scale tornadoes. Measured force and pressure data were then used to judge whether tornado-resistant design for residential structures is feasible. The tornado-induced wind loads were measured on scaled models of buildings in a laboratory-simulated tornado with a core diameter (56 m) and relatively high swirl

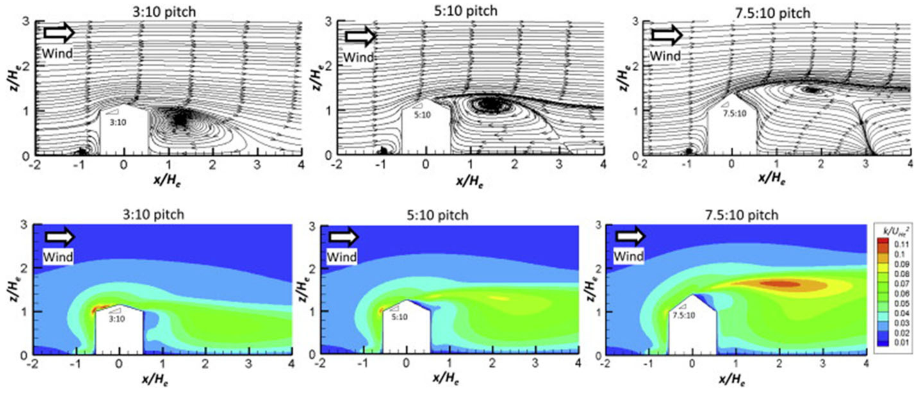


Fig. 18 Interaction between airflow and a generic building profile Adapted from Tominaga et al. (2015)

ratio (2.6) representing an EF3 tornado. The study found that the peak loads vary as a function of eave height, roof pitch, aspect ratio, plan area, and other differences in geometry such as the addition of a garage, roof overhang and soffit. The required strengths of the roof-to-wall and roof sheathing-to-rafter connections were calculated based on the measured loads and compared with their capacities to assess the possibility of failure. It appears that the design of the two critical roof connections in residential construction for tornado-resistant design up to and including EF3 tornadoes can ensure adequate safety cost-effectively by using currently available technology. The influence of swirl ratio, translation speed and building parameters of tornado-induced wind loads on a low-rise building has been deepen by Razavi and Sarkar (2018): the 1:200-scaled building model that was used for this study was located on both sides of the simulated tornado's mean path at several locations up to the distance of several tornado-core radii. At locations where maximum loadings occurred, orientation of the building was changed to explore its effect on peak loads. Results show significantly larger peak load coefficients for the tornado with lower swirl ratio which were comparable to its peak ground surface pressure drop. In spite of a wide amount of studies have been developed or are ongoing, with clear evidence of tornado effects on building and suggestion to ensure safer building, codes and standards do not provide any information on prescriptions and coefficients for adequately take into account additional dynamic pressures caused by the horizontal wind component of tornadoes. For this reason, no verification exists against wind extreme actions, and the generated pressure field causing horizontal actions can significantly increase vertical lift forces if countermeasure are is taken into the design stage.

8 Common vulnerability

The main failure modes due to the action of tornado on existing constructions for buildings are (Fig. 19):

(a) translation or sliding,
(b) overturning,

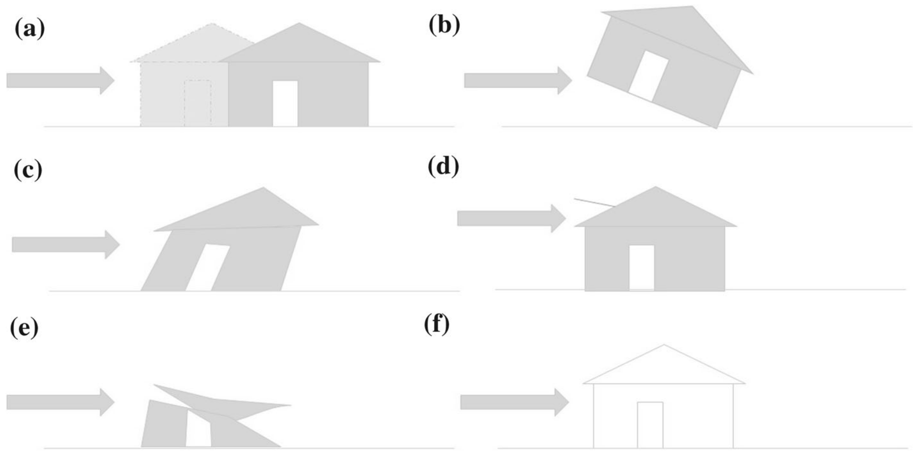


Fig. 19 Main failure modes due to the action of tornado on existing constructions for buildings

(c) racking
(d) material/component failure,
(e) incoming collapse
(f) total destruction.

All these failure modes could be observed both in the recent USA and Italian events, however, depending on the tornado wind force, an increase in the damage loss could be observed. Differences depend mainly on the construction types differentiating USA and Italy: e.g., the diffused wooden houses in USA are often damaged and may be broken also by EF1–2 events, while in Italy where masonry or R.C. frame (reinforced concrete frame) represents the majority of housing constructions, EF3–EF5 are needed to reach the total destruction state. Not only the building type (e.g., the lightness of wooden construction if compared to masonry building) makes US construction more vulnerable to tornadoes, but also the typical construction details of wooden structure diffused in USA (discontinuity between foundation and elevation, discontinuity between roof and elevations of) contribute to this trend. And this is applied also for Italian historical buildings of 500–1000 years of service life (which is not a feature of USA) with massive and heavy typical features. Italian common incremental damages, depending on the increasing EF scale wind action, are mainly represented by roof components failures, upper walls failures, internal devastation, lastly going to the inferior part of the perimeter walls. Examples of every incremental damage observed in the recent events are depicted in Fig. 20. It should be concluded that:

(a) constituent material of structural components could influence both the failure mode, the increasing wind resistance, and the capacity to protect consequently the inhabitants; for this reason, R.C. or masonry buildings showed to be more suitable if compared with wood structures;
(b) connections among structural components is a crucial question, for every type of building; wooden, masonry or R.C. buildings could be seriously damaged if joint are unable to connect the single substructures; internal joint among macro-elements (e.g., roof-upper walls, walls/foundation), but also joint among micro-elements (e.g., brick-to-brick interface in old masonry structures, with a very low content of cementitious materials);
(c) connections among non-structural components are relevant to maintain the building in use in the aftermath and at the same time to ensure the structural functionality; connections between roof cover/upper slab, drainage systems and upper walls are prone to damage seriously even with low wind speed events.

9 Tornado-resistant buildings

A wide amount of research on the designs and practices of tornado-resistant homes exists; however, there is a gap in illustrating alternatives of new construction or retrofit of existing buildings correlating the building technology to the EF Fujita scale of the hypothetical event. The most common resistant building alternative are presented hereafter comparing the building class to the northeast of Italy existing situation. A graphical synthesis of the category class of these building is shown in Fig. 21: every building class is considered to be effectively resistant until the use of inhabitants is ensured, consequently, e.g., while for the F-class the use of the building has been evidenced to be safe only for a EF0 event, the use of A-class building could be considered safe for whatever EF grade.

Fig. 20 Incremental damage observed in the recent Italian events: **a** translation or sliding; **b** overturning; **c** racking; **d** material/component failure; **e** incoming collapse; **f** total destruction

9.1 Class A: Shield buildings, safe room, T.R.B.—EF0–EF5

Safe room (above and below ground), which comprises a strongly constructed escape capsule with a lockable entrance are widely diffused on the market and are commonly able

Fig. 20 continued

to resist up to EF5 (Zhou et al. 2014); with no doubt soil covered safe room (or buildings) are the safest solutions, encompassing the possibility to protect also against debris heavy missiles (FEMA 2015). Shield buildings are a more recent discover: they are represented

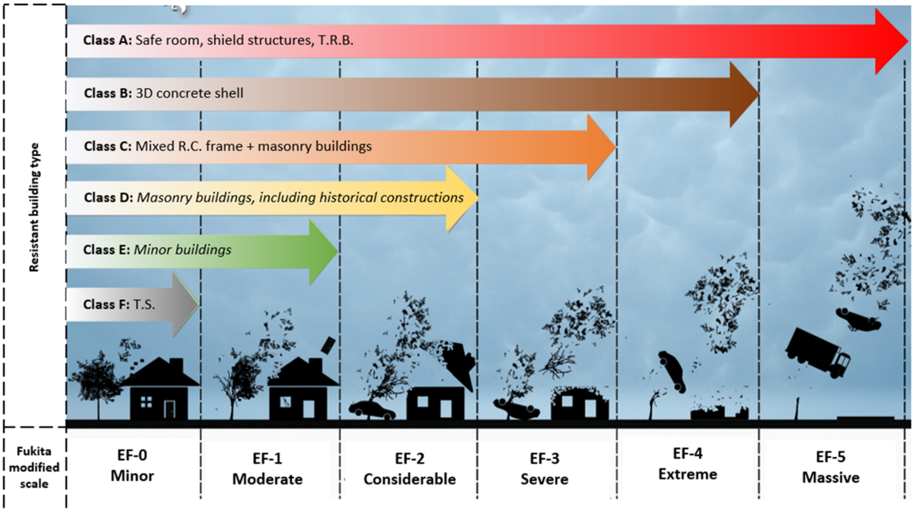


Fig. 21 Tornado-resistant building to a selected EF Fujita scale event, basing onto northeast of Italy events observed in the study

by sacrificial steel or r.c. shield structure, built around existent building. Some first examples were represented by metal sheet covers (Silen 1978) implying however high costs. Gopu and Levitan (2012) presented a low-cost lightwood frame construction for tornado-resistant homes, while Green (Kantamaneni et al. 2017) suggested that a portable pre-fabricated tornado shelter for use in tornado-prone zones. Many solutions exist for tornado building/shelters (Kantamaneni et al. 2017), and all these solutions are adequate to resist to tornado wind forces up to EF4 scale, while for higher speeds (EF5) maraging steel envelope offers an ultimate protection also against heavy flying objects for the whole building which were not provided by existing models (Kantamaneni et al. 2017). Finally, T.R.B. (tornado-resistant building) are included in this category, including structures specifically designed to resist against extraordinary events because of their vital importance in the built environment (nuclear plant, main bridges, etc.). However, all these solutions seem more usable for commercial buildings, industries, and less for housing, due to the inherent design of the protection shield. The existing stock of the northeast of Italy include a very low amount of this building type, and also main infrastructure, hospital and schools should rarely be included into this category.

9.2 Class B: 3D concrete shell—EF0 to EF4

This type of construction requires that a monolithic reinforced concrete shell cover the entire exterior interface (walls, floors, and roofs). This technology is generally well within the capability of most constructors in the precast and tilt-up walls industry but has not been particularly utilized for residential buildings. However, a very few examples of these buildings exist in the northeast of Italy, mainly low-rise buildings.

9.3 Class C: Mixed R.C. frame + masonry buildings—EF0 to EF3

A very common category of building in the northeast of Italy is represented by R.C. frame where some of the structural elevations are built with masonry, with a variable and often uncertain grade of structural capacity. Even though this type of building is not recommended either for the ability to withstand seismic events, nor for durability, nor for high cost; however, this building type is very diffused. Against tornadoes, this class evidenced very different capabilities, partially due to the variable realization of connections (mainly between R.C. and the masonry part), and partially for the different technique used for roofing, which could be R.C., mixed (masonry/R.C.), or wooden made. We can finally conclude that an average behavior has been shown: the capability to resist against up to EF3 event, with the most of damages onto the roof secondary elements. The main of this category is represented by residential or commercial low-rise buildings in the northeast of Italy.

9.4 Class D: Masonry buildings, including historical constructions (> 500 years)—EF0 to EF2

Masonry buildings, both new and historical, exhibited a variety of behavior against tornadoes. For new or recent buildings (construction year > 1950), depending mainly on the number of stories the behavior could change: one story recent buildings could resist up to EF3–4 events, if masonry or mixed masonry/R.C. roof is present; wooden roof changes drastically this capacity, especially when plain wood structures are used, without joints connecting with the elevations. Two or more stories recent buildings exhibited in most of the observed cases a very low capacity to avoid roof extended damages; only recent masonry buildings (construction year > 2000) exhibited the ability to resist against higher wind levels (up to EF3) because of the compulsory presence of R.C. top frame beam (at the interface among main masonry walls and the roof), due to the recent code introduction (NTC 2008), which has been recently updated (NTC 2018). The main number of buildings in the northeast of Italy is included in this category.

9.5 Class E: Minor buildings—EF0 to EF1

Wood frame buildings and agricultural buildings (barns, dairy buildings, dovecotes, farmhouses, farms, grain elevators, granaries, grinding mills, hayracks, post mills, ranches, smock mills, stables, tower mills, watermills, windmills) exhibited a very low capacity to resist against tornado events. The main weakness is represented by constituent light materials (wood, aluminum or thick steel laminates), slender and thick walls and great openings allowing to low-speed wind to pressurize large part of the interior, leading to speedy damage, and resulting often in the roof or large walls collapse. A wide number of agricultural building are present in the northeast of Italy.

9.6 Class F: T.S. (Temporary structures)—EF0

This last class covers the so-called T.S. (temporary structures) which comprises one of the following types: tents used for recreational camping, tents or membrane structures for open-air activities, multiple tents or membrane structures for agricultural use, greenhouses. All these buildings are temporary whenever no particular structures exist to keep them safe from extreme events (e.g., no foundation, no R.C. or steel structures). Whenever at least the foundation R.C. structure is present, the building could be ranked in class “E.” From a wide amount of observations, there are few possibilities to consider safe these structures for EF1 events. A restricted number of building are present in the northeast of Italy.

10 Conclusion

In this study, the tornado events from 1905 to 2017 observed in the northeast of Italy are described and commented upon. After the presentation of the tornado events for the European context, then in particular for the Italian territory, and tornado intensity estimations, the study focus onto retried data from the literature and records tornadoes analyzing in particular three main key points: (a) the damage assessment of the most extreme tornado event recorded in the northeast of Italy, (b) structural codes provisions for tornado and common vulnerability, and finally (c) tornado-resistant buildings. Basing on these analysis the following conclusions could be presented: Italy do not exhibit a particular amount of historical tornadoes, even if some destroying events up to EF5 Fujita scale have been recorded; during the last ten years, not only worldwide, but also in the European and Italian contest extreme wind events are evidently increasing, it is not clear if for climatological causes; there is a strong need to avoid for large tornado disaster in crowded urban areas, preserving not only infrastructures, power plants, hospitals, schools and main industries, but also residential buildings, which has been demonstrated to be the most damaged buildings during tornado in the northeast of Italy during the observed period (1905–2017); common rules coming from observations are presented; however, structural codes and standards must be updated introducing the analysis and verification of structure against extreme wind events in order to preserve the inhabited context from large disaster.

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