Damage characterisation using Sentinel-1 images

Kopiika, Nadiia; Ninic, Jelena; Mitoulis, Stergios

DOI:
10.2749/manchester.2024.0367

Damage characterisation using Sentinel-1 images: Case study of bridges in Ukraine

Nadiia Kopiika, Jelena Ninic, Stergios-Aristoteles Mitoulis

University of Birmingham, UK

Contact: n.kopiika@bham.ac.uk

Abstract

Bridges are vital infrastructure assets, ensuring the economic activity during the adverse times of conflict. Notwithstanding, there is insignificant research regarding their damage characterization with the use of remote approaches for post-conflict recovery. Monitoring and remote sensing is a promising technology for identification of damages caused by war-induced hazards, including artillery fire, explosions and shelling, and hence facilitate accurate and rapid evaluations of capacity and functionality loss, providing valuable information for reliable risk assessments at emergency and normal circumstances. The geospatial analysis, based on Interferometric SAR (InSAR) products of coherence, calculated between SAR images recorded at different dates could serve as a mean to characterize the level of damage, as demonstrated in this research. The main findings of study include the use fully open-access and remote data for assessment of critical infrastructure damages.

Keywords: bridges; damage; targeted human-induced hazard; explosion; Interferometric SAR (InSAR) products; coherence; recovery; remote monitoring; transport network; functionality.

1 Introduction

Due to vital importance of bridges in linking regions, enabling transportation and fostering economic progress [1] they often become the most targeted assets in war-torn regions. In such circumstances mass bridge destruction is often even more complicated due to limited access to them, resulting in inability of rapid assessment, decision-making and post-conflict recovery. On-site inspection and testing, which are typical approach for damage detection and retrofit decision-making, are increasingly time- and resource consuming, as well as difficult in accessibility, thus this survey method cannot be implemented effectively [2]. Remote sensing can serve as a substitute for identifying structural damage in aftermath or during the conflict due to ability to detect alterations across extensive areas and its quick revisitation as well as high potential to reduce the necessity for on-site surveys, which is the issue for conflict-affected areas that may be challenging to access [3]. This capability gap is of specific importance for ensuring of resilience and sustainability of infrastructural systems, revealing the necessity of research on remote assessment approaches. Recent years, modern remote techniques, including Earth Observation (EO) and geospatial approaches and especially Synthetic-Aperture Radar (SAR) images have gained remarkable popularity for effective management of large portfolios of structures in post disaster regions [4][5][6]. In particular, one of the most effective approaches is associated with the use of Coherent Change Detection (CCD), by comparing alterations in the landscape before and after significant events which could be represented in a form of phase signal correlation of InSAR products [7]. This enables efficient damage evaluation in hazard-affected regions for further recovery decision-making. Although there is a number of works, covering the use of InSAR products for damage detection, the war-induced damages of bridges, which are different in their nature, formation and development are not sufficiently represented in international literature. This gap of knowledge requires additional attention for post-conflict recovery giving motivation of this study.

1.1 Data

As the initial source of data for remote damage characterization in this study were used open-access Setinel-1 Single Look Complex (SLC) products and OpenStreetMap (OSM) data, obtained for the period of interest (the expected time of the most intense destruction in the region, - time of military hostilities in Kyiv region). As the initial data for further processing served 3 Sentinel-1 mission interferometric wide swath (IW) SAR images in ascending and descending geometry for the time period of the interest (February-March, 2022). The Sentinel-1 mission products are described in more detail in[8],[9] and this mission is dedicated to serve primarily medium to high resolution applications through a main mode of operation that features both a wide swath (250 km), high geometric (5 m×20 m) and radiometric resolution with the 12 days` revisit time. SLC images were used with 2.3 m pixel spacing in the slant range, 14.1 m in azimuth, translated to 5 m in ground range and 20 meters in azimuth resolution. [9]. The dataset of bridges for assessment was created with the use of OpenStreetMap (OSM), which provides publicly accessible geospatial data in global scale regarding networks and infrastructural assets for both commercial and research applications. Thus, the location of bridges within the boundaries of the selected study area was identified with the use of OSM database by application of filters, which indicate assets crossing the Irpin river. Following, the range of area of interest (AOI) was specified for downloading Sentinel-1 radar images.

1.2 Methodology for damage characterisation

General stages of processing of Sentinel-1 products for characterization of damages are included in the workflow (see Figure 1).

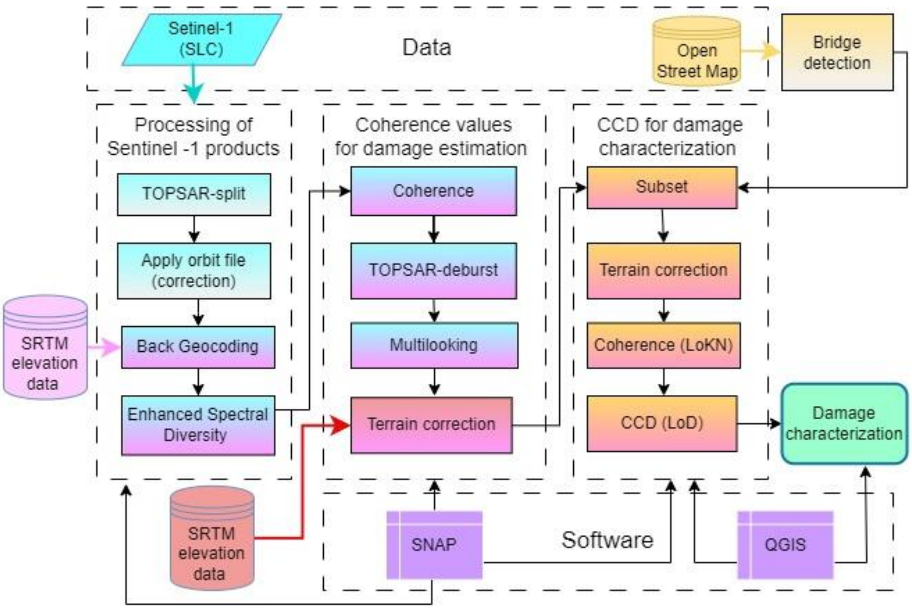

Figure 1. Workflow for damage characterization with the use of Sentinel -1 products

1.2.1 Processing of Sentinel -1 products

Processing of Sentinal-1 SAR SLC images was done with the use specialized software Sentinel Application Platform (SNAP)[10]. At the first stage the specific pre-processing operation was applied for two interferometric pairs before and after the invasion (19.01.2022 -12.02.2022 and 19.01.2022 - 01.04.2022). While each SAR pair requires its own processing workflow, in order to semi-automate the process and avoid saving interim products, the GraphBuilder tool was used. Thus, for IW mode 1 sub-swath and 3 bursts of Sentinel-1 products were used using the terrain observation with progressive scans SAR (TOPSAR) split method. Following, orbit file correction of products is applied in order to ensure best geo-positional accuracy using the 'SRTM 1Sec HGT' method. Subsequently, the Back-Geocoding operator is used for coregistration of the two products using the Digital Elevation Model of Shuttle Radar Topography Mission SRTM-1 arcsec. Coregistration in this case referred to the alignment of master and slave images, the pixels of the slave images corresponding to those of the master and representing an identical area (see Figure 2). Following, a constant range offset for each burst using a small block of data in the center of the burst and a constant azimuth offset are estimated (Enhanced Spectral Diversity operator) and bursts are averaged to get the final constant range and azimuth offset for the whole image [11],[12].

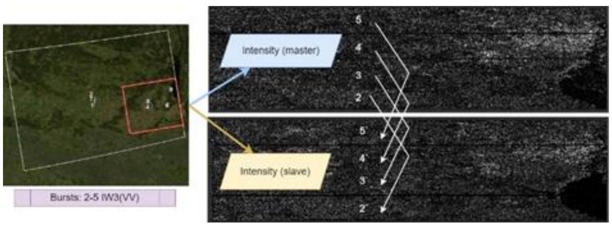

Figure 2. Coregistration of master and slave products (bursts 2-5).

At the next stage the processing of each of coregistered products, containing the intensity bands of 2 images, included the coherence estimation, indicating the level of correlation of pixels between the master and slave images, and 'deburstіng' to remove the gaps and merge bursts, preserving the phase information. Following steps include mulitlooking to reduce the inherent speckle noise that originally appears to the SAR images and the Terrain Correction to convert the radar coordinates into geographic (geocoding). Geocoding operation is intended to compensate distortions due to topographical variations of a scene and the oblique viewing angle of the satellite sensor. Finally, spectral subsets of coherence products are created using WKT-format to indicate area of interest of each assessed bridge.

1.2.2. Coherence values for damage characterization

Damage characterization in this study was completed on the basis of Interferometric SAR (InSAR) products of coherence. InSAR complex coherence correlation was calculated for the stacks of two images which allowed colocation of spatially overlying SAR products with the resampling of pixel values into the geographical raster. According to[11],[13] coherence values can be considered as a similarity measure of the interferometric SAR returns between two acquisitions, quantifying the magnitude of complex correlation between two SAR images from different dates. Thus, the complex coherence is derived with the use of following Eqn (1):

$$\rho = \frac{E(s_1 s_2^*)}{\sqrt{E(s_1 s_1^*)E(s_2 s_2^*)}}, \qquad (1)$$

where s1 and s2 are the corresponding complex pixel values, and E() indicates the expected value and, * is the complex conjugate operator.

Coherence values range is within from 0 (low coherence) to 1 (high coherence). If the responds of the pixel scatters are similar, then the coherence is high [13] and these pixels are characterized as stable with very small variations over time, while low coherence values indicate certain changes. Thus, decorrelation (changes in the backscattered signal of the satellite) is reflected in coherence values decrease and could be considered as a sign of damage/destruction of the asset [7].

Therefore, for characterization of damages, induced by certain event, two pairs of coherence products are utilized: two images (ρ) acquired before the event (pre), and two images before and after the event (post). The SAR Coherence Change Detection (CCD) can be defined by Egn(2):

$$CCD = \rho(pre) - \rho(post) \in [-1 \dots 1], \quad (2)$$

where positive values of CCD represent areas with significant differences, values close to zero indicate relatively stable areas between satellite passes, and negative values could be related to the appearance of new stable areas during the interval between the two coherence products.

For further geographical colocation, illustration and comparative analysis of obtained results of damage detection, they are exported to QGIS environment. The CCD values for studied assets were classified to identify those, with potentially high damage level, taking into account the level of uncertainty due to low resolution of Sentinel-1 products.

2 Results and discussion

2.1 Case study

In the aftermath of the full-scale Russian invasion on the territory of Ukraine on February 24, 2022, the Ukrainian civil infrastructure confronted a relentless onslaught comprising missile attacks, artillery bombardment and shelling. It is worth noting that the Kyiv region, operating as a pivotal defensive bulwark for the capital, Kyiv, bore the brunt of this considerable aggression. During the inaugural months of the conflict, between February-March 2022, bridges within this region assumed a paramount strategic role in both offensive and defensive military operations, as was emphasized by Daniel Rice (the President of American University in Kyiv)[14]. In particular, certain bridges spanning the Irpin river were targeted to impede the Russian forces from advancing towards Kyiv via vital routes including, but not limited to Bucha-Kyiv, Hostomel-Kyiv, and Irpin-Kyiv. The emphasis on the pivotal function of bridges in the context of this conflict has effectively rendered the Irpin river a natural barricade, thwarting any further expansion of military activities.

Furthermore, it is imperative to underscore that the armed forces placed considerable reliance upon these bridge structures, recognizing them as integral components of logistical routes crucial for the transportation of substantial supplies and ammunition. This heightened recognition accentuated the significance of bridges as primary targets within the military context, according to points presented in [15].

Of equal importance, bridges served as crucial routes for facilitating the evacuation of civilian populations through humanitarian corridors. Regrettably, during this period, these critical conduits were subjected to targeting by Russian forces, as depicted in Figure 3 [16]. As a consequence of these circumstances, the pivotal role played by these bridges in the region, coupled with the considerable damage sustained, served as the primary motivation for the case study within the ambit of this research.

a) *b)*

Figure 3. Evacuation routs for civilians in Kyiv region, targeting by Russian forces obtained from: a) social networking, b) satellite imaginary.

Subsequent to the cessation of the most intense hostilities in the Kyiv region and the relocation of the front line to the south-east, the bridges across the Irpin river have assumed a pivotal role as essential elements within the logistics network, facilitating the interconnection of various economic regions of the country with the capital. From this point of view, they play important role in the operational efficiency of Ukraine's industrial and agricultural sectors.

With 55% of its land dedicated to arable use, Ukraine stands as one of the leading agricultural producers worldwide. Therefore, any disruption to its logistical networks would result in adverse global ramifications at both regional and international levels. This contributes to the significance of the bridges of Kyiv region, Ukraine as the case study in this research.

Therefore, the case study for illustration of methodology for damage characterization includes 17 bridges in Kyiv region, crossing the Irpin river, identified with the use of OpenStreetMap geospatial data in the Area of Interest (AOI). Coordinates and parameters of examined bridges are presented in Figure 4 and Table 1.

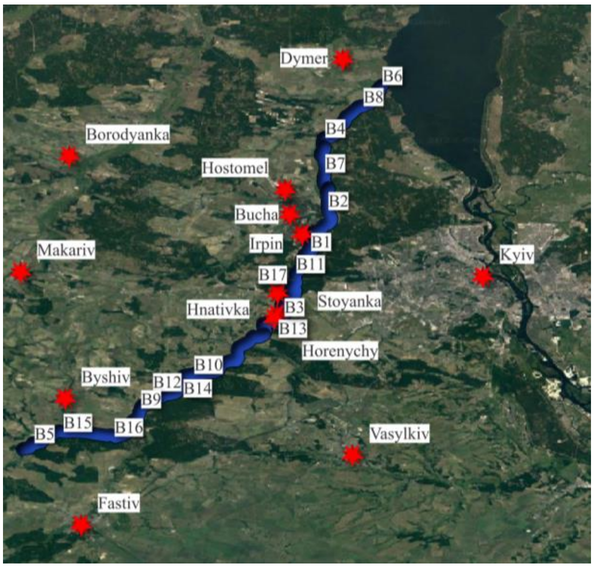

Figure 4. Bridges of the case study in AOI

Table 1. Coordinates and dimensions of bridge structures in the AOI

Asset ID	Length/ Width [m]	Lon, Lat	
1	90/24	50°29'29,680" N 30°15'28,934" E	50°29'27,063" N 30°15'33,716" E
2	140/27	50°33'12,613" N 30°17'8,608" E	50°33'12,017" N 30°17'2,319" E
3	85/10	50°23'28,229" N 30°13'5,070" E	50°23'28,590" N 30°13'3,212" E
4	35/8	50°39'51,805" N 30°16'51,514" E	50°39'52,292" N 30°16'50,869" E
5	36/9,9	50°11'50,698" N 29°50'10,434" E	50°11'52,097" N 29°50'10,523" E
6	155/10	50°44'36,703" N 30°22'8,149" E	50°44'40,140" N "30°22'6,879" E
7	41/9	50°36'39,687" N 30°16'50,213" E	50°36'39,872" N 30°16'49,264" E
8	60/19	50°42'44,851" N 30°20'22,571" E	50°42'49,559" N 30B°20'19,429"E
9	87/11	50°15'0,959" N 29°59'59,243 " E	50°15'1,344" N 29°59'58,128" E
10	34/4,5	50°18'11,437" N 30°4'49,621" E	50°18'12,102" N 30°4'49,269" E
11	25/4,2	50°27'25,228" N 30°14'12,463" E	50°27'24,733" N 30°14'13,572" E
12	23/7	50°16'20,038" N 30°2'32,858" E	50°16'20,753" N 30°2'32,248" E
13	24/2	50°22'49,958" N 30°11'12,009" E	50°22'50,667" N 30°11'12,114" E
14	25/3	50°17'16,262" N 30°3'31,742" E	50°17'16,219" N 30°3'33,732" E
15	22/8	50°12'52,507" N 29°52'49,863" E	50°12'52,984" N 29°52'49,809" E
16	15/4	50°12'26,815" N 29°57'31,024" E	50°12'27,351" N 29°57'31,782" E
17	173/30	50°26'50,775" N 30°14'7,284" E	50°26'50,593" N 30°14'4,834" E

2.2 Damage characterisation for the case study bridges

In general, 17 bridge structures were examined with the use of methodology described above. Thus, changes in coherence detection (CCD) between 2 pairs of Sentinel-1 products were used as an indicator of particular level of damage. Noteworthy, due to the constraints associated with the use of low-resolution Sentinel-1 images, some assets exhibited insufficient image resolution, resulting in low coherence values in each image pair. Nonetheless, the proposed algorithm exhibited promising results for some of bridges. In order to assure reliability of results and decrease uncertainty for assessed structures ranging was used. Bridges were categorized based on their Level of Knowledge (LoKn), signifying the degree of result reliability contingent upon the image resolution. Consequently, structures were allocated into groups of low (L), medium (M), and high (H) LoKn. Furthermore, according to calculated CCD, each asset was assigned with deterioration index, depending on the Level of Damage (LoD), -similarly, L, M, H (low, medium and high). For precise numerical values of coherence, CCD and classification within this case study, reader can refer to Table 2, while Table 3 identifies, which range limits were used for grouping of assets according to assumed reliability of results.

Table 2. Damage characterization with the use of Sentinel-1 SAR coherence products: results for the case study

No	Coherence (before/after)		CCD		LoKn	LoD
	2σ	Max	2σ	Max		
1	0,816/ 0,501	0,829/ 0,517	0,523	0,632	H	H
2	0,859/ 0,611	0,967/ 0,829	0,499	0,540	H	H
3	0,625/ 0,437	0,651/ 0,461	0,375	0,384	M	M
4	0,229/ 0,211	0,376/ 0,295	0,118	0,241	L	L
5	0,633/ 0,387	0,652/ 0,389	0,333	0,387	M	L
6	0,876/ 0,717	0,889/ 0,754	0,144	0,390	H	L
7	0,567/ 0,527	0,570/ 0,558	0,142	0,156	M	L
8	0,359/ 0,433	0,436/ 0,435	0,112	0,115	L	L
9	0,889/ 0,330	0,890/ 0,338	0,666	0,730	H	H
10	0,469/ 0,506	0,469/ 0,506	- 0,145	- 0,145	L	-
11	0,588/ 0,526	0,588/ 0,526	0,280	0,280	L	L
12	0,504/ 0,446	0,526/ 0,456	0,188	0,189	L	L
13	0,406/ 0,346	0,505/ 0,401	0,087	0,178	L	L
14	0,406/ 0,231	0,505/ 0,313	- 0,029	0,062	L	L
15	0,567/ 0,264	0,683/ 0,376	0,350	0,400	M	M
16	0,549/ 0,204	0,567/ 0,208	0,349	0,359	L	L
17	0,821/ 0,747	0,941/ 0,756	0,351	0,521	H	H

Table 3. Range limits for classification of assets.

LoKn	Coherence(Max)	Coherence(2σ)
H (High)	0.75-1	0.7-1
M (Medium)	0.55-0.75	0.5-0.7
L (Low)	0-0.55	0-0.5

Additional clarification of the LoKn and LoD indexes is given in *Figure 5* and *Figure 6*.

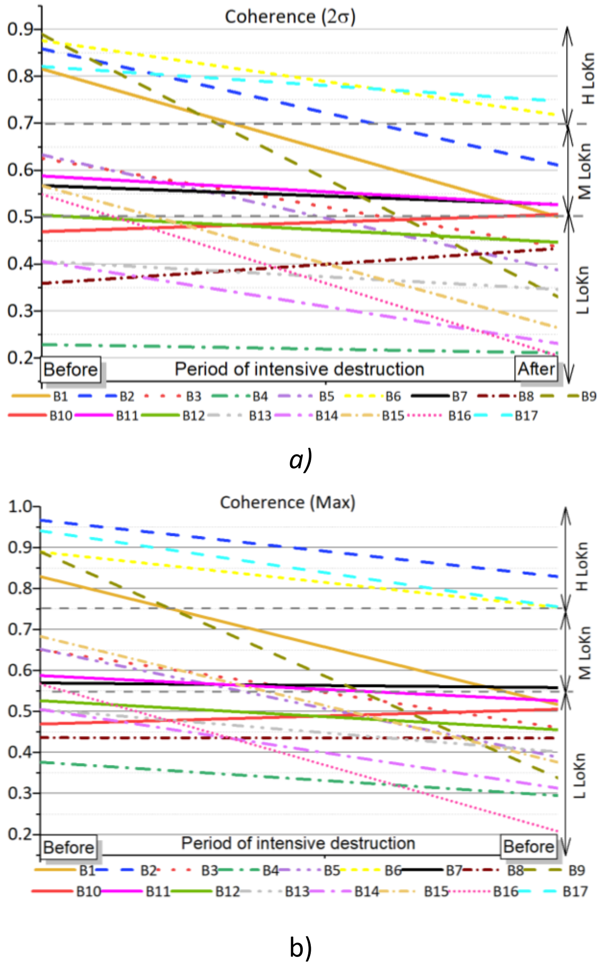

Figure 5. Coherent Change Detection (CCD) for examined bridges: a) 2σ-values, b) maximum values

Calculated values of coherence reveal a consistent overall pattern of decrease during the examined period of time, however to different degree (LoD). Nevertheless, results for different assets are associated with significantly different levels of uncertainty (LoKn), as shown by Table 2, *Figure 5*For example, for bridges B1, B2, B9, B17 coherence between pre-event images exceed 0,7, which could serve as an indicator of sufficient reliability of data. However, for bridges B10-B14, estimated coherence values are lower than 0,5, which reveales low quality of initial products.

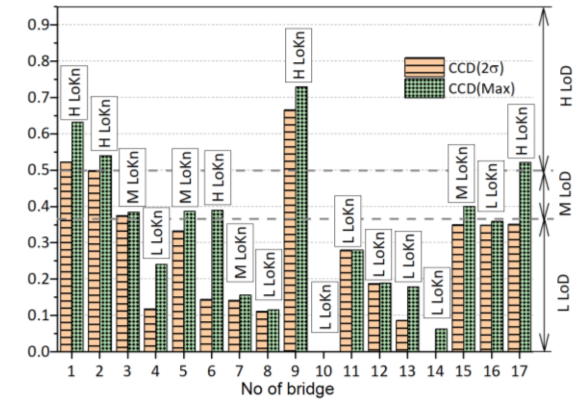

Figure 6. The level of reliability of damage characterization according to Coherent Change Detection (CCD)

Hence, it is important to take into account the level of certainty of damage detection results for their further implementation and decision making. Notwithstanding, the level of evidence concerning the quality and precision of these findings should be considered as they may not adequately represent damage characteristics of the bridge. Therefore, in order to eliminate the influence of low quality of results, classification from Table 3 is used and assets with Level of Knowledge (LoKn) that fall below a certain threshold are excluded from further consideration, as their reliability is insufficient to make any assumptions about the level of damage (LoD).Final results of coherence change for bridges with reliably estimated values are presented in *Figure 6*.

In particular, CCD results could serve as an indicator of the extent to which the missile attacks within February -March 2022 led to the deterioration of bridge structures in the area of interest (Irpin region). Specifically, these structures can be categorized based on the degree of damage according to ranges, which are outlined in Table 4.

Table 4. Values of LoD of examined bridges and their ranging.

LoD	CCD (Max)	CCD (2σ)	Note
H	0,5-1	0,4-1	Total destruction of whole structure or some of the components
M	0,35-0,5	0,3-0,4	Considerable damages in some of the components
L	0-0,35	0-0,3	General deterioration, signs of moderate/low damages

As shown on Figure 1, further illustration of estimated indications of damages on examined assets is processed in QGIS environment (see *Figure 7* for different LoD and High LoKn).

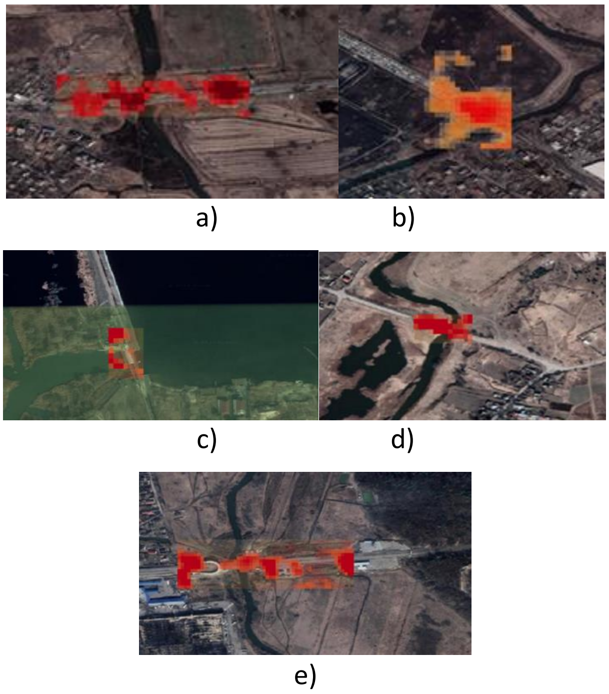

Figure 7. Damage characterisation according to CCD values at H LoKn: a) H LoD (B1); b) H LoD (B2); c) L LoD(B6); d) H LoD (B9); e) H LoD (B17)

2.3 Uncertainties and limitations in damage assessment.

Damage detection and characterization in bridges with the use of remote approaches is associated with comparatively high level of uncertainty with potentially high impact on safety. Although, some of common assessment uncertainties (e.g. material properties, hidden damages, modelling assumptions) are not applicable in this discussion, there some obscurity sources and limitations which could be eliminated in further research. One of the most influential in this study is data uncertainty due to low spatial resolution of Sentinel-1, thus the described method is applicable only for big in area structures. In particular, according to obtained results, it could be assumed, that the use of Sentinel-1 radar products could be used for rough damage characterization for assets with length above 80-90 m. Moreover, in each particular case study should be taken into account additional impacts of weather air conditions, precipitation and time of year, which could also distort the results. The issue of reliability of these results was partly addressed by filtering of data according to LoKn, however some uncertainty remained. This problem could be further overcome by utilizing high spatial resolution images from commercial satellite missions. However, commercial satellite missions acquire images in response to demand, which means that obtaining pre-event SAR images could not always be possible. In addition, when considering case studies with war-induced damages, commercial satellite images during the conflict are often unavailable due to sensitivity issues. Another important aspect, which has to be considered in the assessment with the use of radar data, are dynamic changes of the environment, and thus, changes of coherence, not associated with damages. Therefore, accurate timing of the damage and the use of Sentinel-1 products, the closest to assumed event date are of paramount importance. Also, in this research were used images, captured from satellite from the same angle, thus the line of sight did not have impact on how geometry of assessed objects was depicted on the Earth's surface.

The impact of these uncertainties on safety is substantial. Without appropriate consideration, these unknowns can lead to the underestimation or overestimation of damage, potentially leading to inaccurate safety assessments. To mitigate the effects of uncertainties and ensure the safety of bridge structures, safety margins and precautionary measures should be implemented. Consistent inspections and monitoring play a crucial role in minimizing uncertainties and upholding safety standards. Therefore, authors would like to note, that the described approach is mostly suitable for emergency, remote assessment of structures in limited access conditions, when only open-access data is available. In order to further increase reliability of proposed research additional cross-validation with different method is strongly recommended.

3 Conclusions

The paper proses a novel approach for fully remote damage detection and characterization in bridge structures with the use Setinel-1 Single Look Complex (SLC) products and OpenStreetMap (OSM) data, obtained for the period of interest. In particular, coherence between two pairs of images, representing similarity measure of the interferometric SAR returns between two acquisitions from different dates was used. Thus, changes in coherence detection (CCD) between 2 pairs of Sentinel-1 products were used as an indicator of particular level of damage, where high CCD results were assumed to correspond to areas with considerable differences (damages/deterioration). The general trend towards decrease of coherence values was noted, however reliability of these results differs significantly. Thus, the level of evidence concerning the quality and precision of these findings was taken into account by filtering and elimination of potentially low-quality results, as they may not adequately represent damage characteristics of the bridge. The main findings of study include the use fully open-access and remote data for assessment of structural damages. This is of specific importance for limited access conditions during the conflict, as demonstrated on the case study of bridges destruction in Ukraine.

Acknowledgements

Authors would like to acknowledge of support received from the British Academy for this research (Award Reference: RaR\100770).

4 References

[1] Congress S. S. C., Escamilla J., Chimauriya H., Puppala A. J. Eye in the Sky: 360° Inspection of Bridge Infrastructure Using Uncrewed Aerial Vehicles (UAVs). *Transportation Research Record*,2023, 0(0).

[2] Putri A. F. S., Widyatmanti W., Umarhadi D. A. Sentinel-1 and Sentinel-2 data fusion to distinguish building damage level of the 2018 Lombok Earthquake. *Remote Sensing Applications: Society and Environment*, 2022, 26, 100724.

[3] Markogiannaki, O., Xu, H., Chen, F., Mitoulis, S. A., & Parcharidis, I. (2022). Monitoring of a landmark bridge using SAR interferometry coupled with engineering data and forensics.

International journal of remote sensing, 43(1), 95-119.

[4] Papadopoulos GA., Agalos A., Karavias A., Triantafyllou I., Parcharidis I., Lekkas E. Seismic and Geodetic Imaging (DInSAR) Investigation of the March 2021 Strong Earthquake Sequence in Thessaly, Central Greece. *Geoscience*s. 2021; 11(8):311.

[5] Aimaiti Y., Sanon C., Koch M., Baise L. G., Moaveni B. (2022). War Related Building Damage Assessment in Kyiv, Ukraine, Using Sentinel-1 Radar and Sentinel-2 Optical Images. Remote Sensing, 14(24), 6239.

[6] Geudtner D., Winter R., Vachon P.W. Flood monitoring using ERS-1 SAR interferometry coherence maps. Proc. *IEEE IGARSS*,1996, 966-968.

[7] ElGharbawi T.; Zarzoura F. Damage detection using SAR coherence statistical analysis, application to Beirut, Lebanon. *ISPRS Journal of Photogrammetry and Remote Sensing*, 2021, 173,1-9.

[8] Potin P., Rosich B., Grimont P., Miranda, N., Shurmer I., O'Connell A., Torres R., Krassenburg, M. (2016, June). Sentinel-1 mission status. In Proceedings of EUSAR 2016: 11th European conference on synthetic aperture radar, VDE, 06-09 June 2016, Hamburg, Germany, 1-6.

[9] Torres R., Snoeij P., Geudtner D., Bibby D., Davidson M., Attema E., Potin P., Rommen B. O., Floury N., Brown M., Traver I.N., Deghaye P., Duesmann B., Rosich B., Miranda, N., Bruno C., L'Abbate M., Croci R., Pietropaolo A., Huchler M., Rostan F., GMES Sentinel-1 mission. *Remote Sens. Environ*, 2012, 120, 9–24.

[10] EoPortal. SNAP (Sentinel Application Platform) toolbox. [Internet]. [cited 2023 Oct 11]. Available from: https://www.eoportal.org/other-space-activities/snap-sentinel-application-platform#snap-sentinel-application-platform-toolbox

[11] Serco Italia SPA. RUS Lectures. Lebanon Damage Assessment with Sentinel-1 & Sentinel-2. (version 1.1), 2020 [cited 2023 Oct 15] Available from: https://rus-copernicus.eu/portal/the-rus-library/train-with-rus/

[12] Serco Italia SPA RUS Lectures. Watching a Typhoon with Sentinel-1 (SNAP), (version 1.1), 2019 [cited 2023 Oct 15] Available from: https://rus-copernicus.eu/portal/the-rus-library/learn-by-yourself/

[13] Chatterjee R. S., Lakhera R. C., Dadhwal V. K. InSAR coherence and phase information for mapping environmental indicators of opencast coal mining: a case study in Jharia Coalfield, Jharkhand, India, *Canadian Journal of Remote Sensing*, 2010, 36:4, 361-373.

[14] Daniel Rice. Ukrainian Bridges are Playing a Vital Role in Both the Defense and the Offense in the Ukrainian-Russian War. Small wars journal, 2022 [cited 2023 Oct 15]. Available from: https://smallwarsjournal.com/jrnl/art/ukrainian-bridges-are-playing-vital-role-both-defense-and-offense-ukrainian-russian-war

[15] Maria Engqvist. A Railhead Too Far: The Strategic Role of Railroads during Russia's Invasion of Ukraine, Russia and Eurasia Studies programme, 2022, [cited 2023 Oct 13] Available from: (https://www.foi.se/rest-api/report/FOI%20Memo%207954)

[16] Lee Brown. New York Post: Kyiv fears air raid as mass graves are dug in 'apocalyptic' Mariupol, 2022 [cited 2023 Oct 10] Available from:https://nypost.com/2022/03/09/kyiv-fears-attack-as-mass-graves-being-dug-in-mariupol/