engineering proceedings

MDPI

Proceeding Paper

Degradation Monitoring of Reinforced Concrete Structures by NDT: Laboratory and Field Applications †

Amirhossein Askari [1,*], Lisa Furlan [1], Federica Zanotto [2], Fabio Minghini [3] and Enzo Rizzo [1]

[1] Department of Physics and Earth Sciences, University of Ferrara, 44122 Ferrara, Italy; lisa.furlan@edu.unife.it (L.F.); enzo.rizzo@unife.it (E.R.)
[2] Department of Engineering, Corrosion and Metallurgy Study Centre "A. Daccò", University of Ferrara, 44122 Ferrara, Italy; federica.zanotto@unife.it
[3] Department of Engineering, University of Ferrara, 44122 Ferrara, Italy; fabio.minghini@unife.it
* Correspondence: amirhossein.askari@unife.it
† Presented at the 1st International Online Conference on Non-Destructive Testing, 1–3 July 2026; Available online: https://sciforum.net/event/ICNDT2026.

Abstract

This study integrates two non-destructive testing (NDT) techniques—Ground Penetrating Radar (GPR) and Ultrasonic Pulse Velocity (UPV)—to evaluate RC bridge columns. Two real cases were investigated. The first is an old column, without original design drawings, recovered from a demolished bridge and tested in the laboratory. The second is a circular column from a bridge in service, with known design, used to validate the rebar position against the theoretical model. By combining the two methods, GPR reconstructed the 3D reinforcement cage while UPV assessed the concrete quality, providing information that a single technique cannot give alone.

Keywords: non-destructive testing; Ground Penetrating Radar; Ultrasonic Pulse Velocity; reinforced concrete bridges

1. Introduction

Modern infrastructure relies heavily on reinforced concrete (RC) structures, which form the backbone of construction worldwide. Among these, bridges play a vital role in connecting areas and allowing the mobility of people and goods [1]. Over time, however, these structures degrade due to mechanical loading, material aging, and—the most important factor—corrosion of the steel reinforcement [2]. For this reason, assessing their condition is essential to ensure structural safety, optimize maintenance costs, and extend service life.

Visual inspections can only detect surface anomalies, and traditional inspection methods are often destructive, time-consuming, subjective, and limited to small parts of the element. In contrast, non-destructive testing (NDT) methods evaluate the internal condition of structures without causing any damage, in a short time, at low cost, and with high resolution [3].

However, each NDT method has its own strengths and limitations. This makes the integration of different NDT techniques especially valuable. Recent studies show that combining NDT methods can improve diagnostic accuracy, reduce uncertainties, and provide a more comprehensive and quantitative understanding of the structural condition [4]. In recent years, research has increasingly focused on the fusion of multiple NDT techniques [5,6], and on deep-learning approaches for automatic GPR interpretation and structural health monitoring of aging bridges [7–10].

Check for updates

Academic Editor: Fabio Tosti

Published: 5 November 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Building on these integrated approaches, this study focuses on two complementary NDT methods: Ground Penetrating Radar (GPR) and Ultrasonic Pulse Velocity (UPV). GPR locates the steel reinforcement and reconstructs the internal geometry of the element, while UPV assesses the quality of the concrete [11]. To demonstrate the value of this combined approach, both methods were applied to two real bridge columns with different characteristics: an old column tested in the laboratory, and a new column tested in the field. The aim is to show how the integration of GPR and UPV can support the condition assessment of RC bridges. In this way, the paper builds a baseline structural model (the reinforcement geometry and concrete integrity) as a first step toward corrosion monitoring.

2. Materials and Methods

2.1. Case Studies

Two reinforced concrete bridge columns were investigated in this study. The first column (Figure 1a) originally belonged to a skew bridge in the Province of Padua, Italy, constructed in 1931 and demolished in 2025; one column was recovered and stored at the University of Ferrara, where it was characterized in the lab (Figure 1b). It is characterized by 60 × 50 cm in cross-section, and about 2 m long. Since original design drawings were unavailable, visual inspection revealed the presence of eight longitudinal plain rebars.



Figure 1. (**a**) The Ponte delle Galle bridge; (**b**) The recovered column was removed from the bridge (red circle indicates the original location).

The second column (Figure 2) was tested in situ as part of a viaduct in Ferrara, Italy, built in 1979 and retrofitted between 2018 and 2023. It has a circular cross-section with a diameter of 1.20 m. According to available documentation, its reinforcement consists of

20 longitudinal ribbed rebars, an external reinforcing spiral with 25 cm pitch and internal reinforcing rings spaced every 1.0 m.



Figure 2. The more recent viaduct in Ferrara, Italy, as it appears following the retrofitting interventions. The red circle indicates the investigated column.

2.2. Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is based on the propagation of high-frequency electromagnetic waves, which are reflected at boundaries between materials with different dielectric permittivity (e.g., the concrete and steel interface) [11]. In this study, data were acquired using the IDS C-Thrue instrument equipped with a 2.0 GHz antenna (IDS Georadar-Part of Hexagon, Pisa, Italy). The electromagnetic wave velocity was estimated using hyperbola fitting and reflections from rebars at known depths. Data were recorded with a time window of 15 ns for the old column and 20 ns for the new one, using 512 samples per trace (time increment ≈ 0.029 and 0.039 ns, respectively) and a trace increment of about 1.4 mm for both surveys. Data processing and 3D modelling were conducted using ReflexW (version 9.5.7), custom Python (version 3.14.6) scripts and ParaView (version 9.1.1) software.

2.3. Ultrasonic Pulse Velocity (UPV)

Ultrasonic Pulse Velocity (UPV) testing measures the travel time of high-frequency longitudinal stress waves propagated through concrete between a transmitter and a receiver over a known distance. The calculated pulse velocity is correlated with the characteristics of the concrete [12]. In this study, measurements were performed using a Proceq Pundit PL-200 instrument (Proceq SA, Schwerzenbach, Switzerland) with transducers of 54 kHz frequency. The instrument was zeroed on its reference calibration bar before each measurement session.

3. Results and Discussion

3.1. Old Bridge Pier

3.1.1. GPR

A 3D GPR investigation was carried out with several parallel lines. Therefore, a measurement grid with five-by-five cm spacing was set up on the three available surfaces of the pier. Figure 3a shows a longitudinal B-scan from the top surface after the following processing flow: Move start time, Band pass butter worth, Background removal, Manual gain (y), Fk migration (Stolt), Time cut and Envelope. Each purple point corresponds to

a reflection from a stirrup. Figure 3b shows a time slice C-scan of the top of the column, generated by combining all the B-scans in ReflexW, and the strong purple lines highlighted the reinforcement grid.

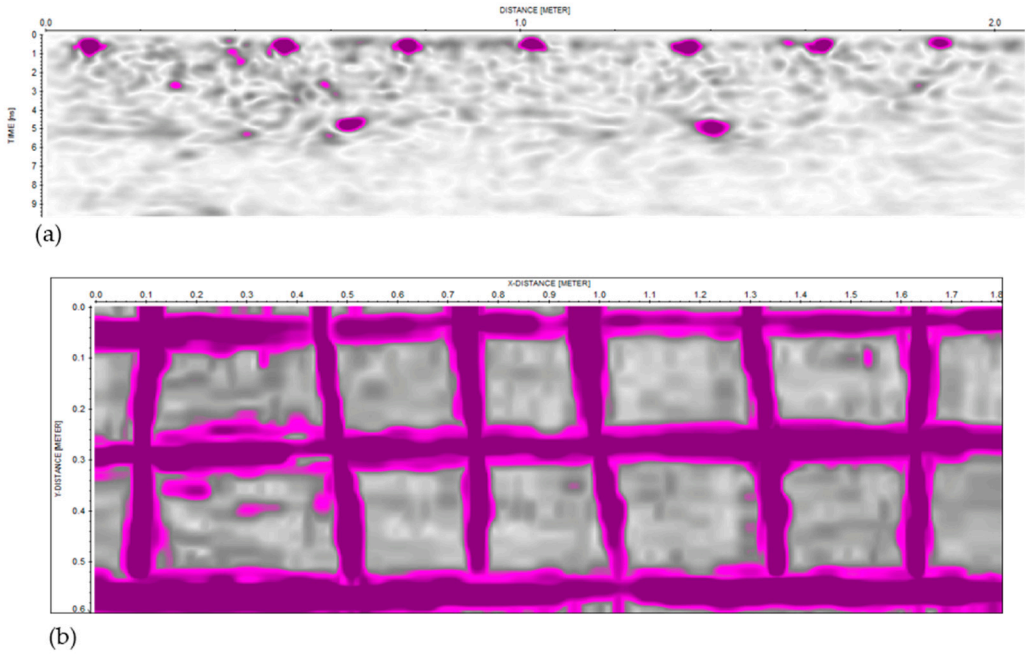

Figure 3. Results from ReflexW: (**a**) B-scan from the top surface; (**b**) time-slice C-scan of the top of the column (the reinforcement grid appears as purple lines).

This process was repeated for all three available surfaces. To reconstruct the 3D reinforcement cage, the processed data of the three faces were exported from ReflexW as ASCII-3D_DATA files, and a fixed amplitude threshold of 3000, selected to keep only the strong reflections from the reinforcement, was applied. Each face was then placed in a common coordinate system using the known column dimensions, and the three sets were merged into a single point cloud, which was visualized in ParaView. The workflow is summarized in Figure 4. As a result, Figure 5 shows the reconstructed 3D rebar cage, where the spacing between the stirrups and longitudinal bars, as well as the concrete cover, can be measured from the model.

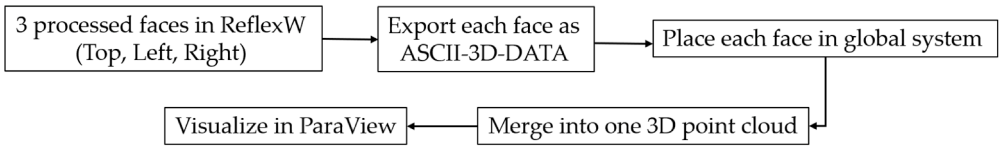

Figure 4. Flowchart of the 3D reconstruction workflow.

3.1.2. UPV

The UPV measurements were conducted at the center of each cell of a 5 cm grid in direct transmission. Figure 6 shows the velocity distribution over the column surface, where the values are classified into five quality classes: Very Poor (<2000 m/s), Generally Poor (2000–3000 m/s), Questionable (3000–3500 m/s), Generally Good (3500–4500 m/s), and Excellent (>4500 m/s) [11]. The results show that at one end of the column the velocity is higher than in the other parts (Figure 6). This zone corresponds to the part of the column that was permanently submerged, while the opposite part corresponds to the splash zone. The higher velocities measured in the submerged part suggest that the concrete in this zone is denser and in better condition than in the splash zone. This observation is consistent with

the general behavior reported for structures exposed to alternating water levels: in the splash zone, concrete undergoes repeated wetting–drying and freeze–thaw cycles and is therefore more prone to deterioration, whereas in the permanently submerged zone, the reduced oxygen exposure limits corrosion and the degree of damage is generally lower [13–15]. However, this interpretation should be confirmed through complementary tests, such as core sampling, carbonation depth measurement, or rebound hammer testing.

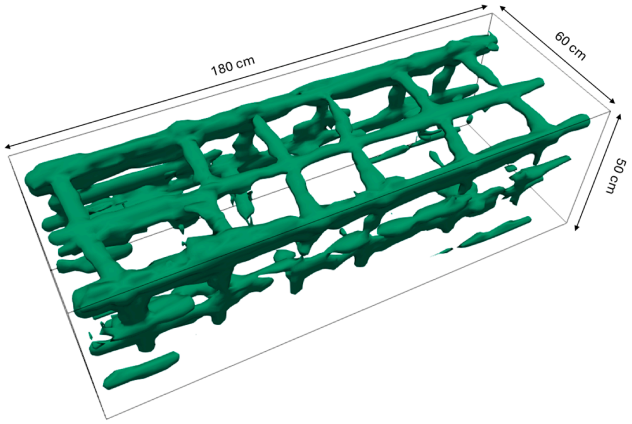

Figure 5. The 3D reinforcement cage visualized in ParaView.

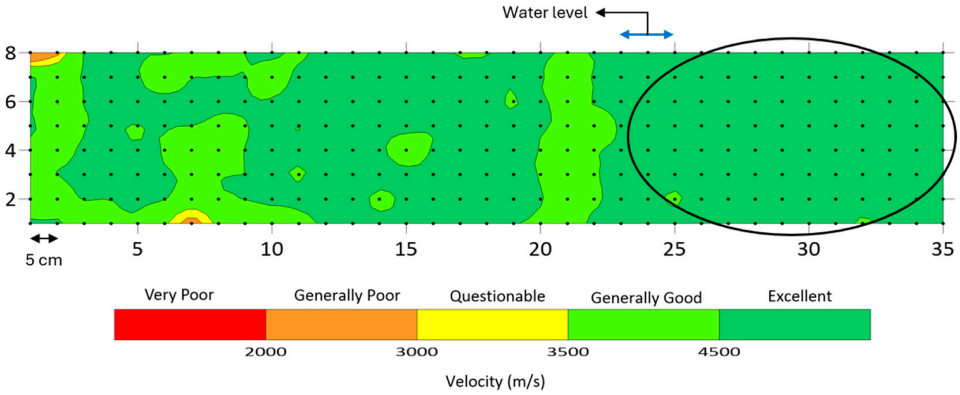

Figure 6. UPV distribution (black dots) over the column surface; the blue arrow indicated the water level boundary separating the splash zone and submerged zone and the circle area marked the high velocity zone.

3.2. New Bridge Pier

3.2.1. GPR

For the GPR survey, a one-meter-tall section in the middle of the column was selected. Two sets of scans were performed: circular scans around the column at different heights, spaced 5 cm apart, and vertical scans along the height at different positions, spaced 10 cm apart. Figure 7a presents a circular B-scan, processed with the same flow used for the old column in ReflexW, where each reflection corresponds to a longitudinal rebar. Using a Python code, the circular scans were converted from Cartesian to polar coordinates (Figure 7b) and merged with the vertical scans to reconstruct the 3D reinforcement cage. Finally, the 3D model was visualized as a point cloud in ParaView (Figure 7c). The 3D model validated the presence of all rebars in the designed drawing. Unlike the old column, the original design of this column was available, which allowed the GPR results to be compared with the known reinforcement layout. The good agreement between them validates the reliability of the method and supports confidence in the reconstruction of the old column, for which no drawings were available.

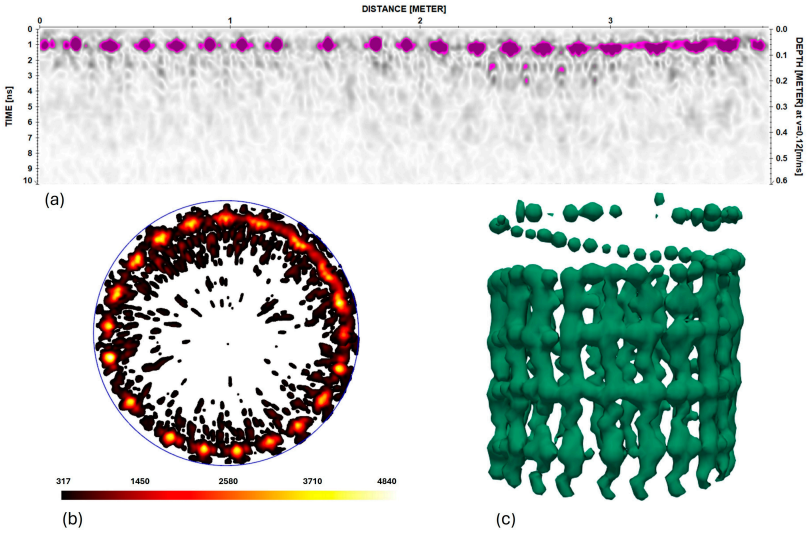

Figure 7. GPR results for the new column: (**a**) circular B-scan from ReflexW; (**b**) polar coordinate conversion from Python; (**c**) 3D reinforcement cage in ParaView.

3.2.2. UPV

The UPV test was applied at 19 points along two different paths on the new column. Figure 8a compares the velocity along the two paths; all values are above 4000 m/s. In addition, Figure 8b,c present the velocity distribution of the points along the two paths. According to the concrete-quality classification based on ultrasonic velocity, all points fall within the Generally Good class indicating a dense and relatively uniform concrete quality. It should be noted, however, that the absolute pulse-velocity values, and thus their classification, can be affected by factors such as curing age, surface moisture and ambient temperature [16,17]. Nevertheless, since all measurements were taken under the same conditions and within a short time, these factors were approximately constant across the points, so the low variation between measurements still supports the relative homogeneity of the concrete.

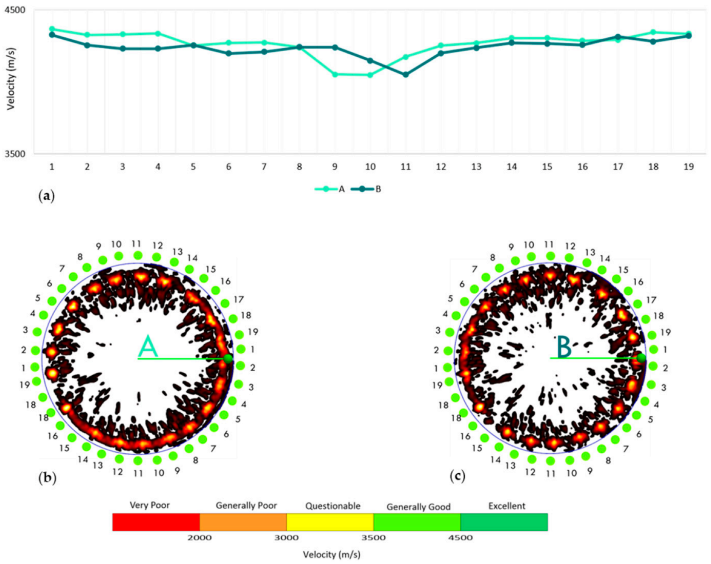

Figure 8. UPV results for the new column: (**a**) Velocity comparison along the two paths; (**b**) Velocity distribution for path A; (**c**) Velocity distribution for path B.

https://doi.org/10.3390/engproc2026156008

4. Conclusions

In this study, GPR and UPV testing were successfully applied to inspect two reinforced concrete bridge columns: an old, demolished column in the laboratory, and a new one in the field.

With GPR, it was possible to completely reconstruct the position of the rebars through ReflexW and to show them in a 3D model thanks to the developed Python code and ParaView. In particular, it was possible to find the rebar positions in the old column without design drawings, and to validate the 3D model using the design documentation of the renovated column.

In parallel, UPV testing permitted the mapping of concrete quality and the identification of weaker structural zones.

Future work will focus on estimating rebar size and type directly from GPR data, rather than just their position. Additionally, electrical resistivity tomography and self-potential will be included to monitor corrosion. The final aim is to integrate these NDT methods with machine learning for faster and automated data interpretation.

Author Contributions: Conceptualization, E.R., F.Z. and F.M.; methodology, A.A. and L.F.; software, A.A.; validation, E.R. and F.Z.; formal analysis, A.A. and L.F.; investigation, A.A. and L.F.; resources, E.R. and F.M.; data curation, A.A. and L.F.; writing—original draft preparation, A.A. and L.F.; writing—review and editing, E.R., F.Z. and F.M.; visualization, A.A.; supervision, E.R.; project administration, F.Z.; funding acquisition, F.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Dataset available on request from the authors.

Acknowledgments: This study was partly supported by FABRE—"Research consortium for the evaluation and monitoring of bridges, viaducts and other structures" (www.consorziofabre.it/en, accessed on 25 July 2026) within the activities of the FABRE-Veneto Strade 2024–2027 research program. Any opinion expressed in the paper does not necessarily reflect the view of the funder. The cooperation of Veneto Strade S.p.A. in permitting the transport from the site of the old bridge to the laboratory of the University of Ferrara is gratefully acknowledged. The design documents concerning the viaduct in Ferrara were kindly provided by Eng. Carlotta Pozzi, on behalf of the Infrastructure and Urban Maintenance Department of the Ferrara City Council.

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

References

1. Boldrin, P.; Fornasari, G.; Rizzo, E. Review of Ground Penetrating Radar Applications for Bridge Infrastructures. *NDT* **2024**, *2*, 53–75. [CrossRef]
2. Fornasari, G.; Capozzoli, L.; Rizzo, E. Combined GPR and Self-Potential Techniques for Monitoring Steel Rebar Corrosion in Reinforced Concrete Structures: A Laboratory Study. *Remote Sens.* **2023**, *15*, 2206. [CrossRef]
3. Capozzoli, L.; Rizzo, E. Combined NDT Techniques in Civil Engineering Applications: Laboratory and Real Test. *Constr. Build. Mater.* **2017**, *154*, 1139–1150. [CrossRef]
4. Capozzoli, L.; Fornasari, G.; Giampaolo, V.; De Martino, G.; Rizzo, E. Multi-Sensors Geophysical Monitoring for Reinforced Concrete Engineering Structures: A Laboratory Test. *Sensors* **2021**, *21*, 5565. [CrossRef] [PubMed]
5. Mukhti, J.A.; Gucunski, N.; Kee, S.-H. Multi-Modal NDE Data Fusion with Machine Learning for Reinforced Concrete Corrosion Damage Classification. *Constr. Build. Mater.* **2025**, *503*, 144557. [CrossRef]
6. Cafiso, S.; Di Graziano, A.; Goulias, D.G.; Pappalardo, G. Data Fusion of Non-Destructive Testing Methods for Bridge Deck Condition Assessment. *Open Transp. J.* **2022**, *16*, e187444782211210. [CrossRef]
7. Hu, D. Deep Learning–Based Framework for Bridge Deck Condition Assessment Using Ground Penetrating Radar. *J. Struct. Des. Constr. Pract.* **2025**, *30*, 04025041. [CrossRef]
8. Khedr, M.; Metawie, M.; Marzouk, M. Integrated Ground Penetrating Radar and Deep Learning Approach for Rebar Diameter Classification in Concrete Elements. *Front. Struct. Civ. Eng.* **2025**, *19*, 524–540. [CrossRef]

9. Jia, J.; Li, Y. Deep Learning for Structural Health Monitoring: Data, Algorithms, Applications, Challenges, and Trends. *Sensors* **2023**, *23*, 8824. [CrossRef] [PubMed]
10. Mostafaei, H. Modal Identification Techniques for Concrete Dams: A Comprehensive Review and Application. *Sci* **2024**, *6*, 40. [CrossRef]
11. International Atomic Energy Agency (IAEA). *Guidebook on Non-Destructive Testing of Concrete Structures*; Training Course Series No. 17; International Atomic Energy Agency: Vienna, Austria, 2002.
12. Jain, H.; Patankar, V.H.; Kulkarni, M.S. *Ultrasonic Testing of Concrete Structures: A Review*; Government of India: Mumbai, India, 2021.
13. Ma, D.; Zhang, M.; Cui, J. A Review on the Deterioration of Mechanical and Durability Performance of Marine-Concrete under the Scouring Action. *J. Build. Eng.* **2023**, *66*, 105924. [CrossRef]
14. Yi, Y.; Zhu, D.; Guo, S.; Zhang, Z.; Shi, C. A Review on the Deterioration and Approaches to Enhance the Durability of Concrete in the Marine Environment. *Cem. Concr. Compos.* **2020**, *113*, 103695. [CrossRef]
15. Ting, M.Z.Y.; Wong, K.S.; Rahman, M.E.; Meheron, S.J. Deterioration of Marine Concrete Exposed to Wetting-Drying Action. *J. Clean. Prod.* **2021**, *278*, 123383. [CrossRef]
16. Güneyli, H.; Karahan, S.; Güneyli, A.; Yapıcı, N. Water Content and Temperature Effect on Ultrasonic Pulse Velocity of Concrete. *Russ. J. Nondestruct. Test.* **2017**, *53*, 159–166. [CrossRef]
17. Godinho, J.P.; De Souza, T.F.; Medeiros, M.H.F.; Silva, M.A. Factors Influencing Ultrasonic Pulse Velocity in Concrete. *Rev. IBRACON Estrut. Mater.* **2020**, *13*, 222–247. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.