Semi-Automated Bridge Inspection using Drones and Deep Learning

Master of Science in Civil Engineering for Risk Mitigation

POLITECNICO MILANO 1863

SCHOOL OF CIVIL, ENVIRONMENTAL AND LAND MANAGEMENT ENGINEERING

Authors:

Zahra Jalali

Pouria Khosravi

Advisor:

Prof. Maria Giuseppina Limongelli

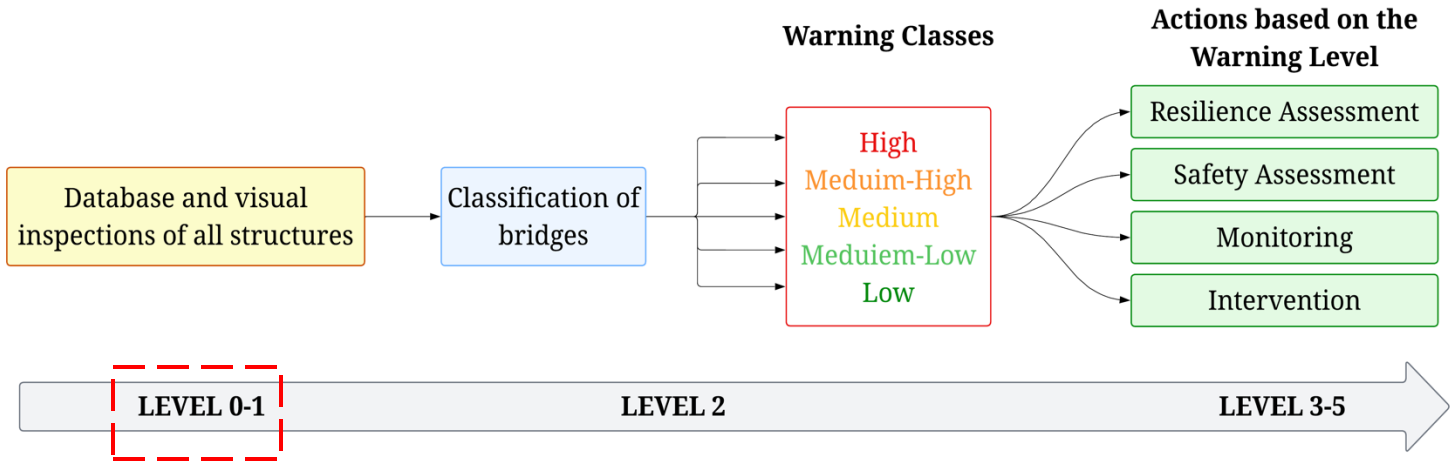
Co-Advisor:

Dr. Tommaso Panigati

Academic Year:
2024-2025

Introduction

"***Guidelines for Classification and Management, Safety Assessment and Monitoring of Existing Bridges***"
Developed to ensure a systematic and standardized approach for assessing the safety and condition of existing bridges across Italy.



Research Scope

01 Drone Survey

- Bridge-wide **aerial data acquisition**
- **High-resolution** imagery acquisition from **multiple angles**
- **Flight path** planning and optimization for **complete coverage**

02 Deep Learning Models

- **Defect detection**
- **Defect segmentation**
- **Model training** for bridge-specific datasets (**Concrete**, **steel** and **masonry**)
- Performance optimization for **real-time processing**

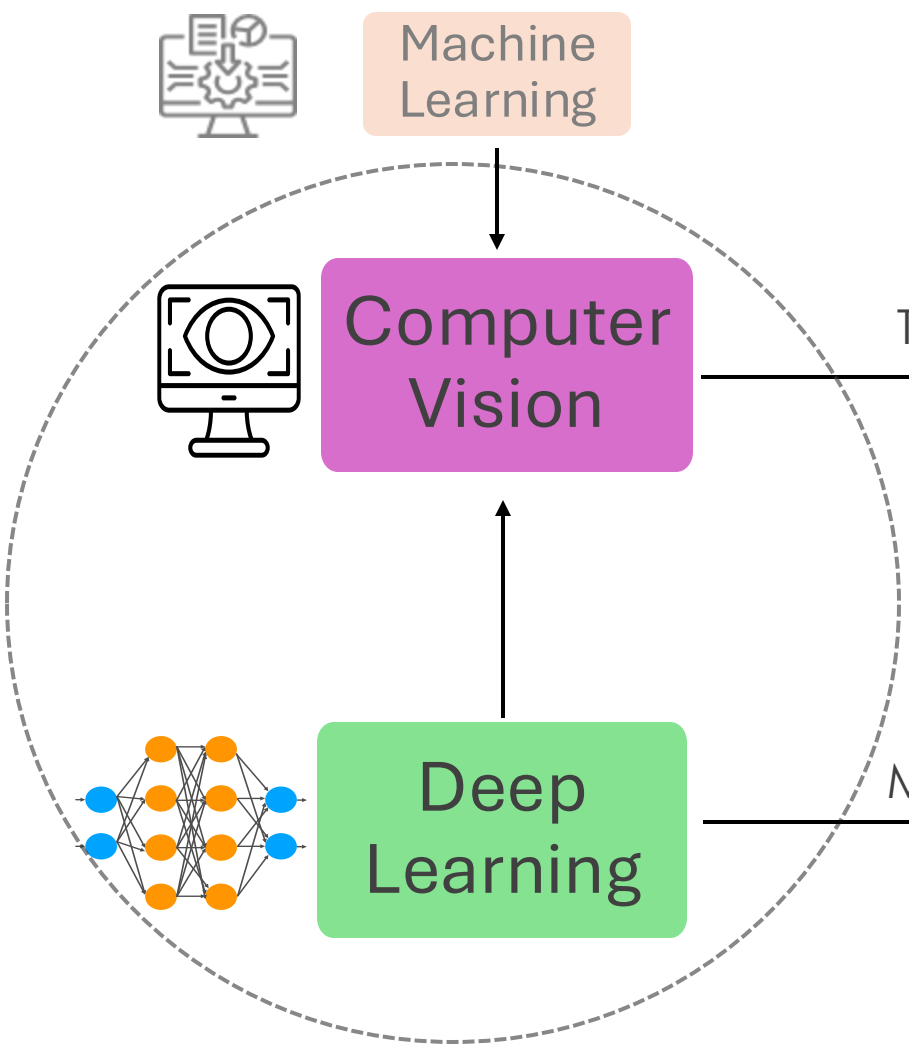
03 3D Reconstruction and Defect Localization

- **3D Reconstruction** of the bridge using **Structure-from-Motion**
- **Spatial mapping of detected defects** in world coordinates

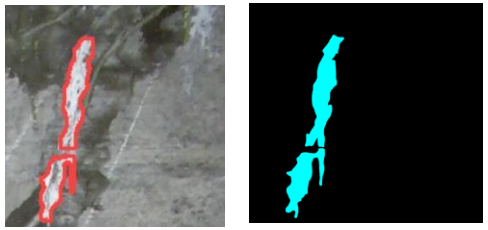
04 Italian Guideline Integration

- Measure **K1 (Extension) & K2 (Intensity)** in real-world coordinates
- **Assess defect severity** in line with **Italian bridge inspection standards**

Computer Vision for Damage Classification



Tasks



Detection + Segmentation

Models

- CNN
- R-CNN
- Fast R-CNN
- Faster R-CNN
- SSD
- **YOLO**

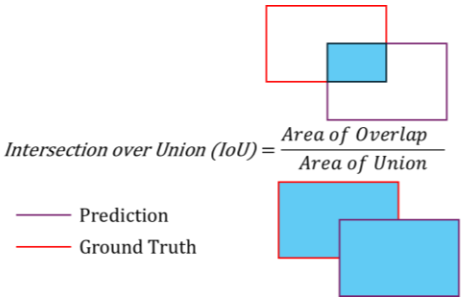
- U-Net
- Mask R-CNN
- **Segment Anything Model (SAM2)**

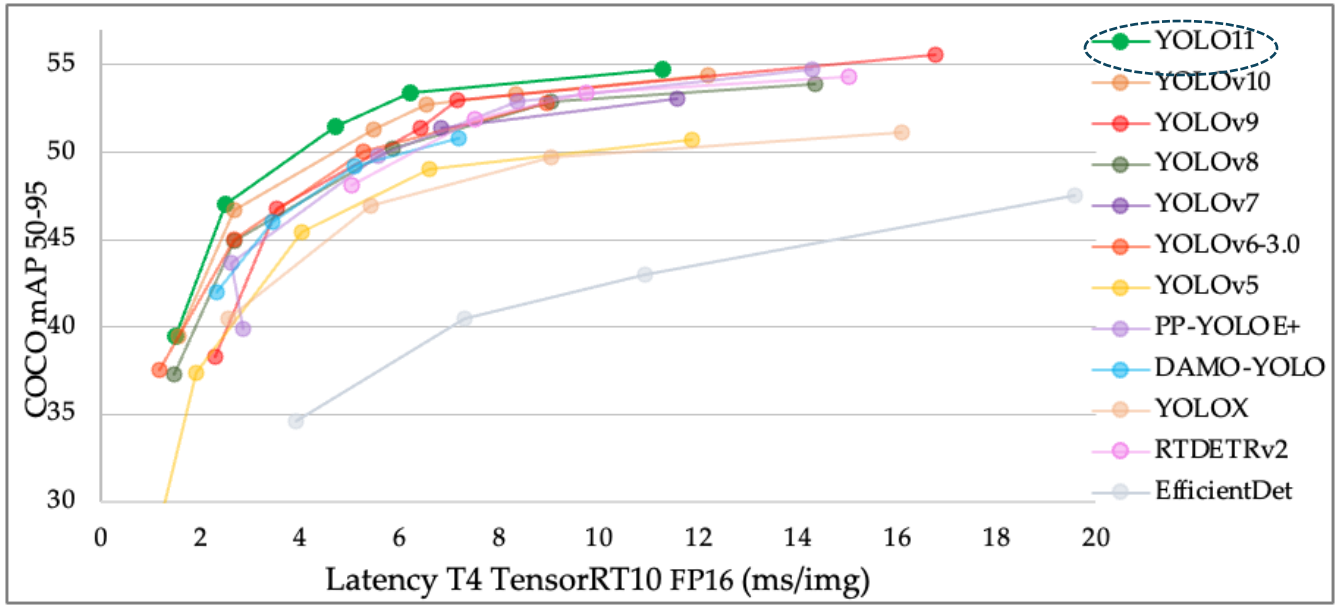
Foundational Architectures Used For Damage Classification

YOLO11 Object Detection

Released September 2024

$$mAP = \frac{1}{n}\sum_{k=1}^{n} AP_K$$





Trained on COCO dataset
(Common Objects in Context)

- 330K images
- 200k images with annotations
- 80 object categories

Yolo11 Model Architecture

Input

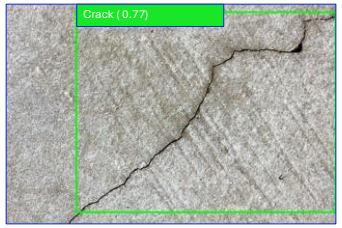
Backbone → **Neck** → **Head**

Feature Extraction using C3K2 Blocks

Combination of multi-scale features using C2PSA

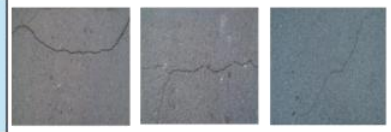
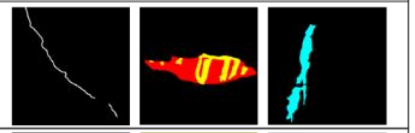
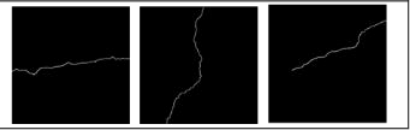
Outputs bounding boxes, confidence, and class

Output



Single Stage Detection= Fast + Near Real time

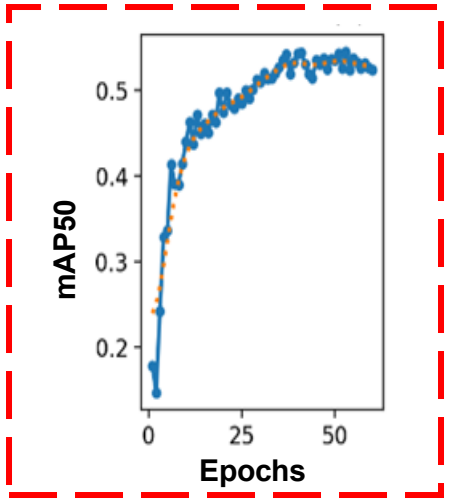
YOLO11 Training Results | Concrete Bridge Defects

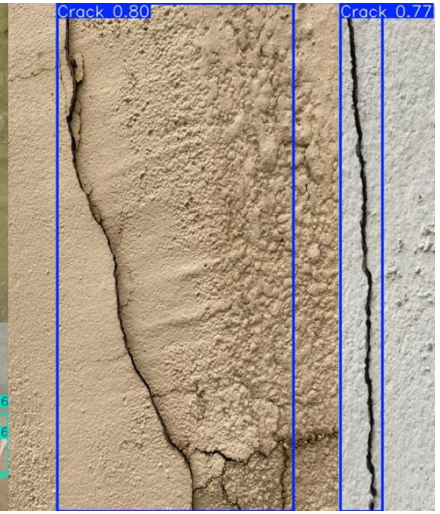
Dataset	RGB Image	Ground Truth
CODEBRIM		
CrackSeg9k		
S2DS		
dacl10k		
Cracktal		

Detection Classes

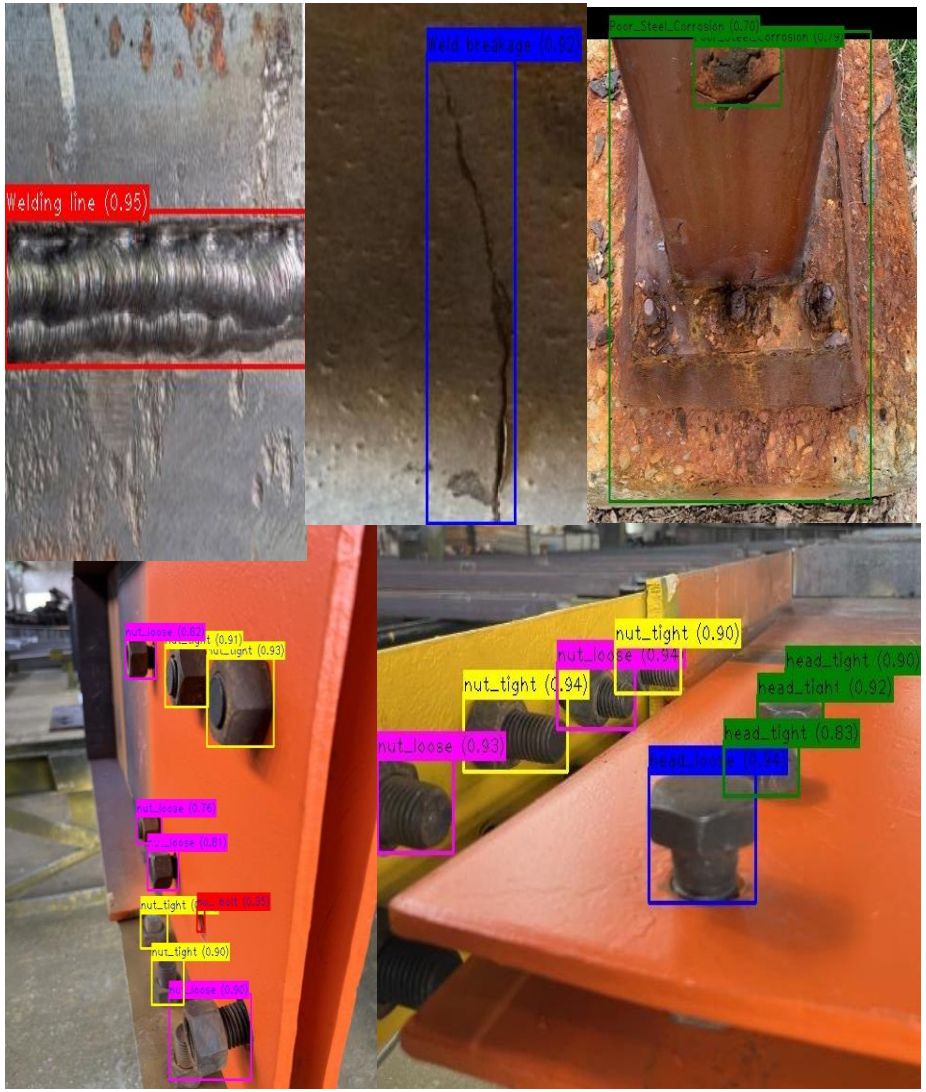
- **Efflorescence**
- **Spalling**
- **Exposed Rebar**
- **Crack**

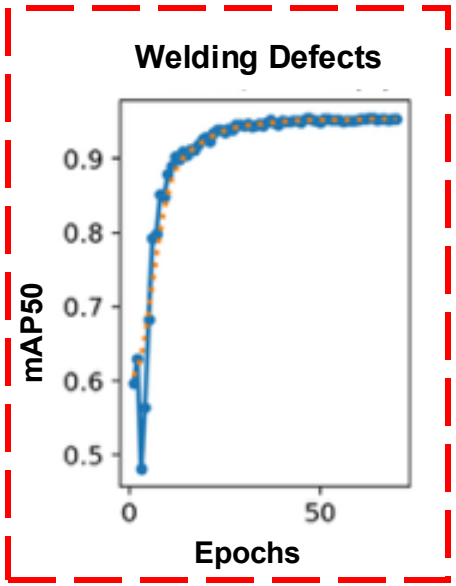
YOLO11m		
mAP@50 (%)	**Epochs**	**Batch Size**
55.25	60	40

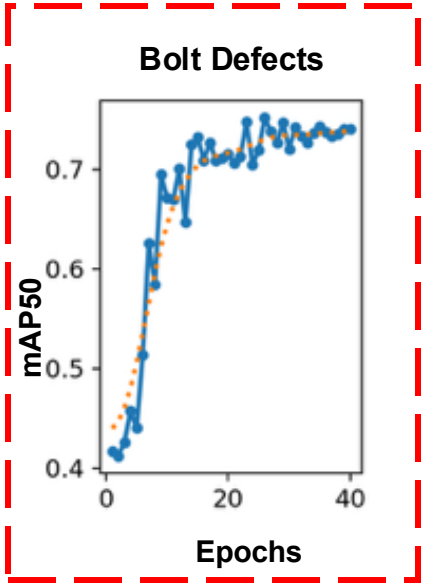


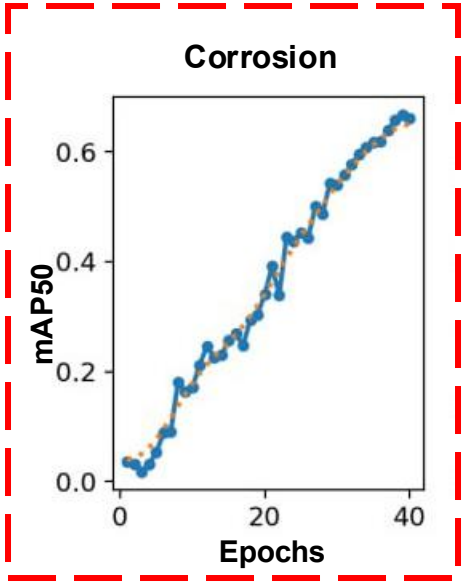


YOLO11 Training Results | Steel Bridge Defects







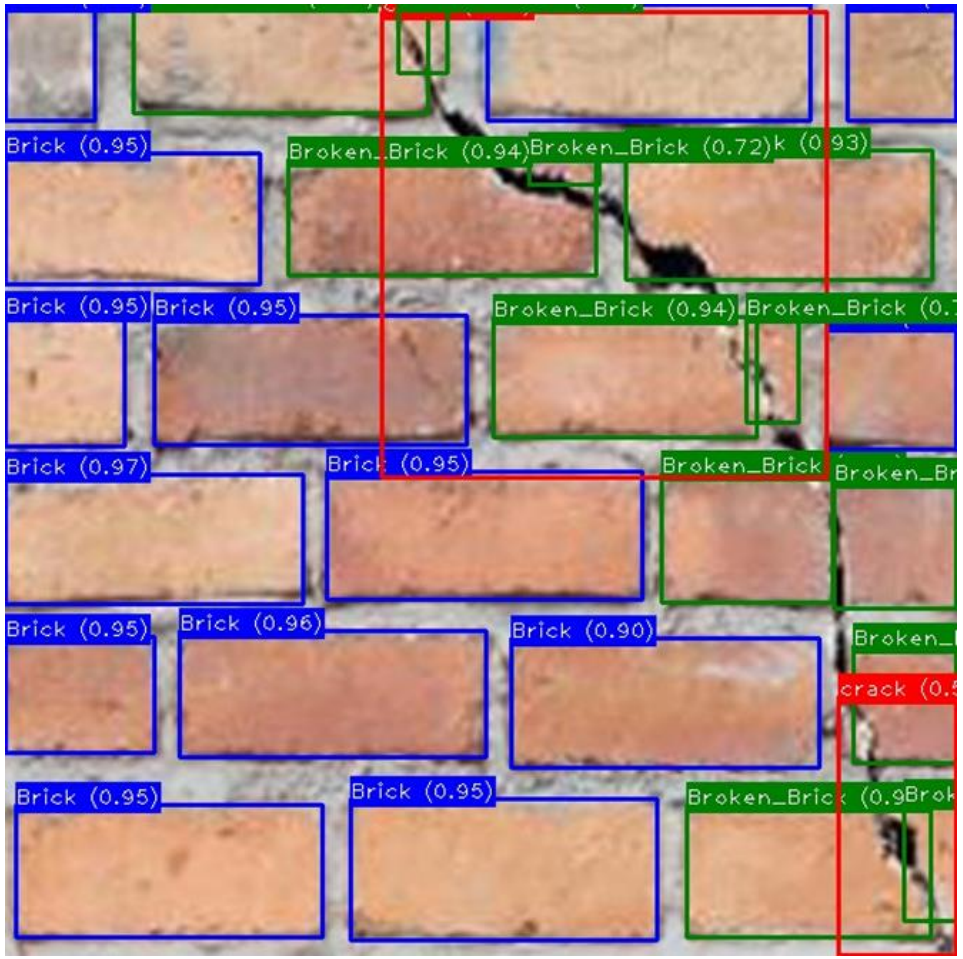


Detection Classes

- **Weld Defect (Porosity)**
- **Weld Breakage (Crack)**
- **Weld Line**
- **Loose Head**
- **Tight Head**
- **Loose Nut**
- **Tight Nut**
- **No Bolt**
- **No Nut**
- **Corrosion**

YOLO11m-Seg		
mAP@50 (%)	**Epochs**	**Batch Size**
95.4	70	40
73.85	40	30
67.4	40	32

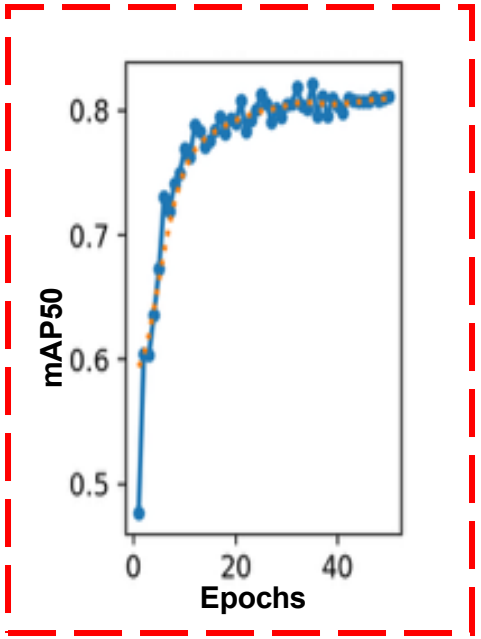
YOLO11 Training Results | Masonry Bridge Defects

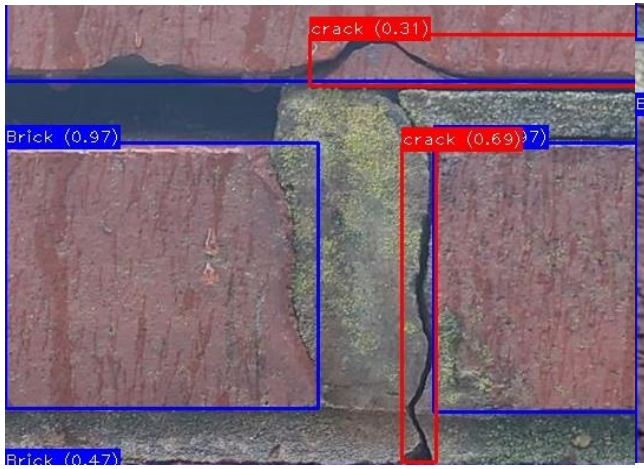


Detection Classes

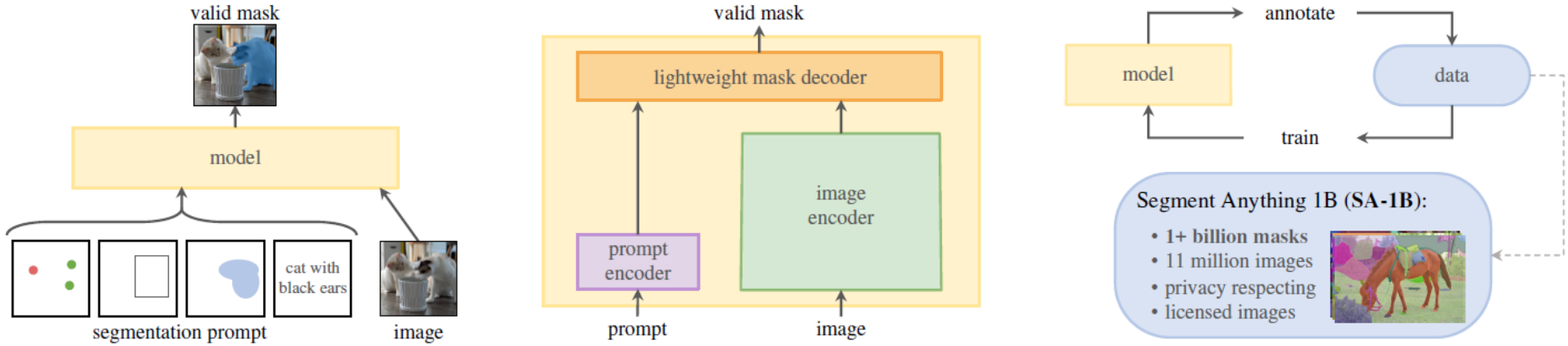
- **Brocken Brick**
- **Crack**
- **Intact Brick**

YOLO11m-seg		
mAP@50 (%)	**Epochs**	**Batch Size**
81.20	50	32





SAM2 Segmentation (Segment Anything Model)

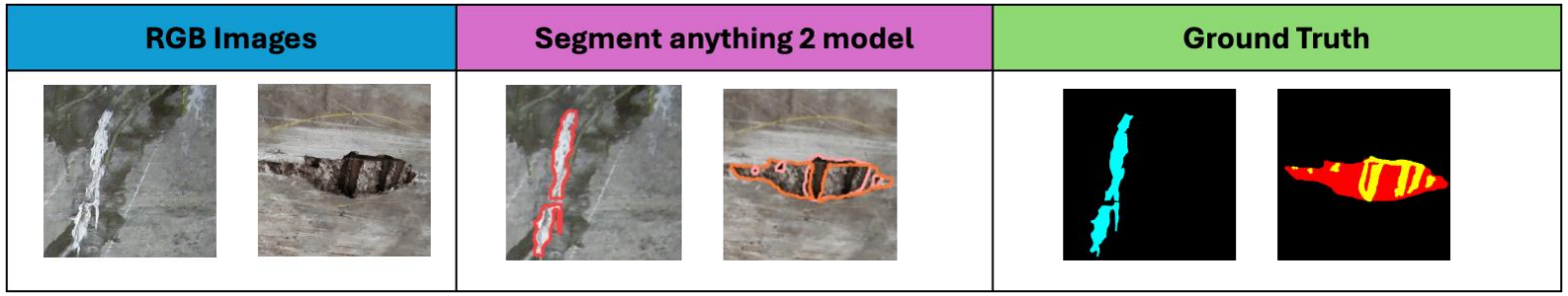


(a) **Task**: promptable segmentation (b) **Model**: Segment Anything Model (**SAM**) (c) **Data**: data engine (top) & dataset (bottom)

- Developed by Meta for universal image segmentation.
- **Zero-shot learning** to segment objects **without specific training**.
- **Prompt-based**, **pixel-level segmentation** model.
- Outputs **precise masks** for defects.

Integration to this research:

- ➢ Segments bridge elements: deck, piers, etc.
- ➢ Links defects to structural components.
- ➢ Used for K1 (extension) measurement.

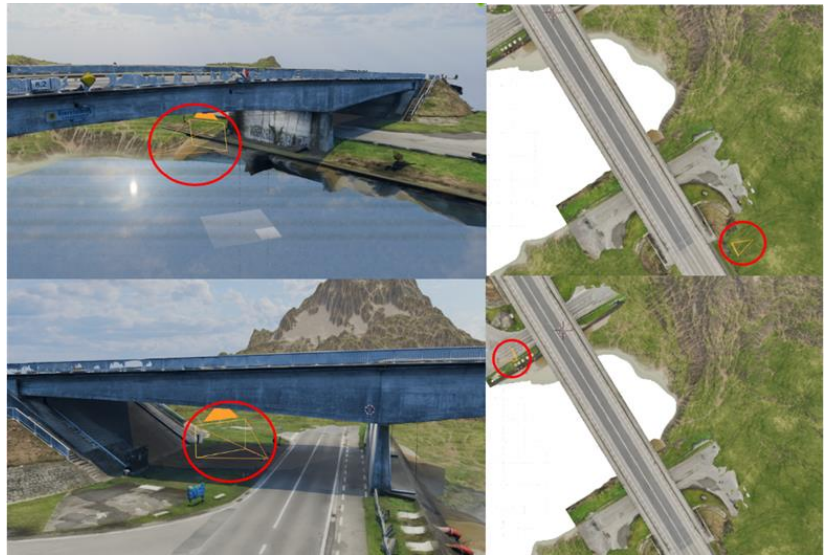


Testing Methodology and Drone flight Simulation

Photogrammetry, conducted by the Geomatics Research Group at KU Leuven, Belgium

Real-time defect detection (YOLO11) and segmentation (SAM2)

3D model for performing simulation



UAV flight path with position marked in red.

Case Study

- **Reinforced concrete overpass** located in Lombardy, Italy
- Selected for: **medium-span layout**, **visible deterioration**, and **accessibility**
- Drone Survey targeted **two spans of the bridge**

DJI Mini 4 Pro

- ✓ 48-megapixel RGB camera sensor
- ✓ Compact and Lightweight
- ✓ Advanced Navigation and Positioning

High Quality RGB Imagery
Resolution: 4032×2268

+

Georeferencing Information

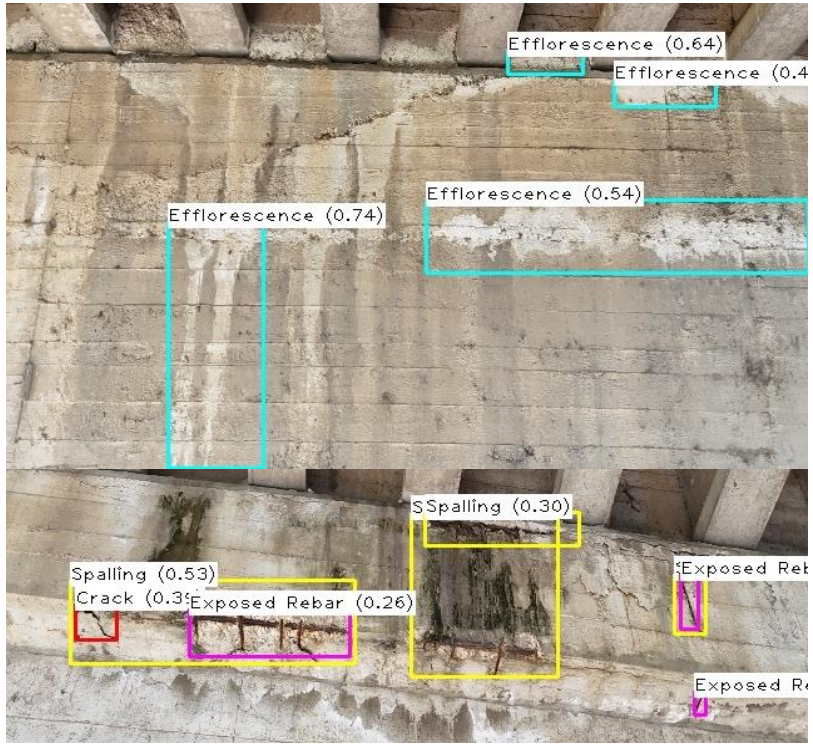
YOLO11 Detection Results

Detection Scope:

- Applied YOLO11 to UAV-acquired imagery of targeted bridge part.
- Targeted primary structural elements: **deck**, **beams**, **abutments**, and **piers**.
- Automated the **classification of severity levels (G).**

Performance Highlights:

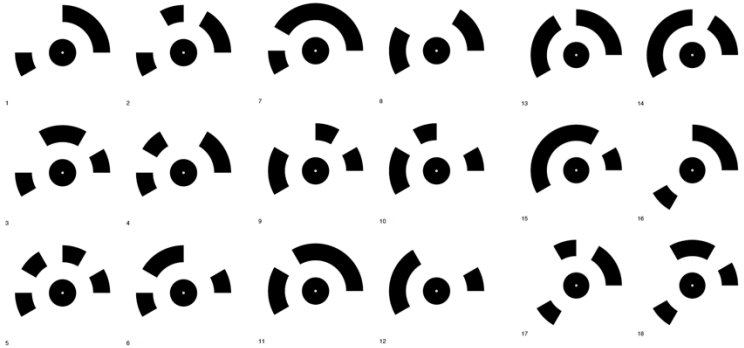
- Detected **multiple defect types** within a single frame.
- **Maintained detection accuracy** under **variable lighting and surface conditions**.
- Enabled **rapid inference**, supporting near real-time analysis.

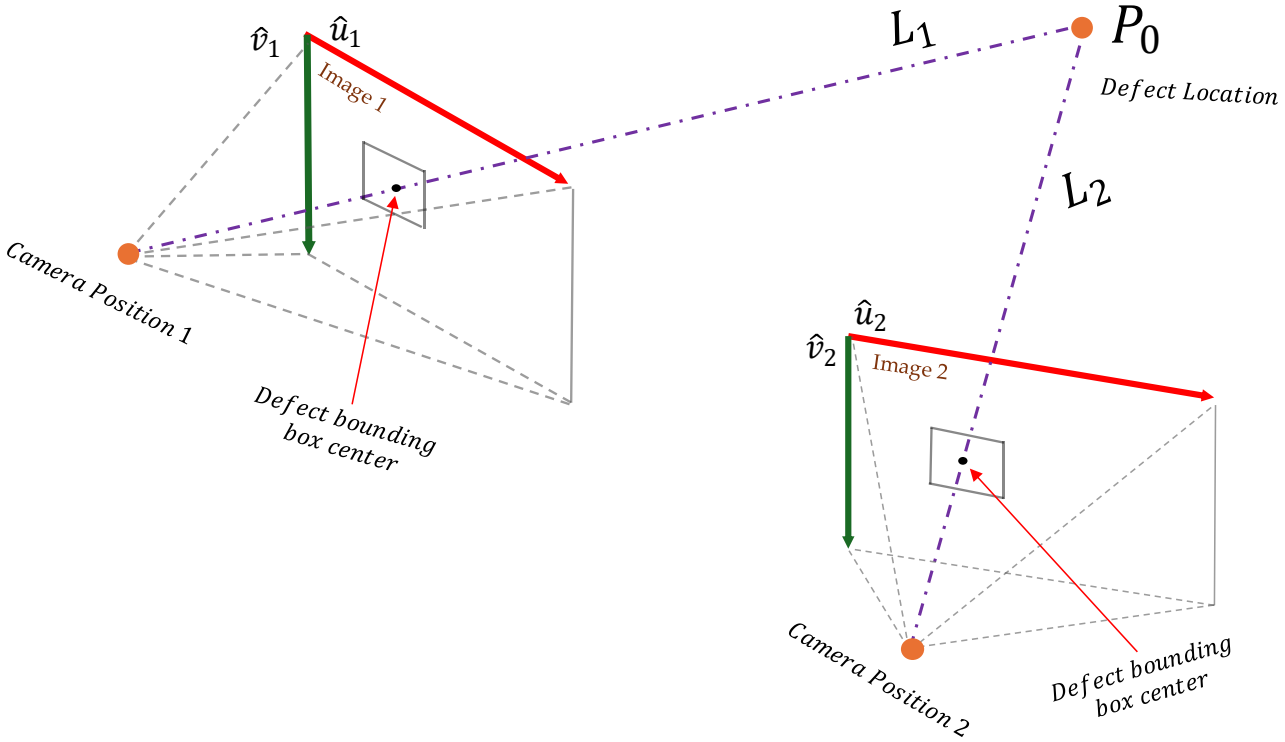


Output frames showing accurate bounding box predictions for structural defects across bridge components.

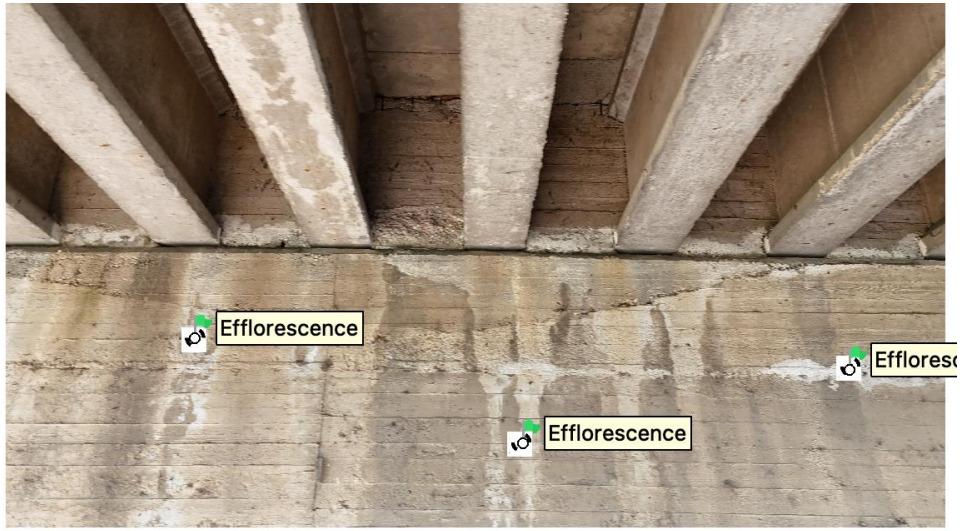
Defect Localization in 3D Model

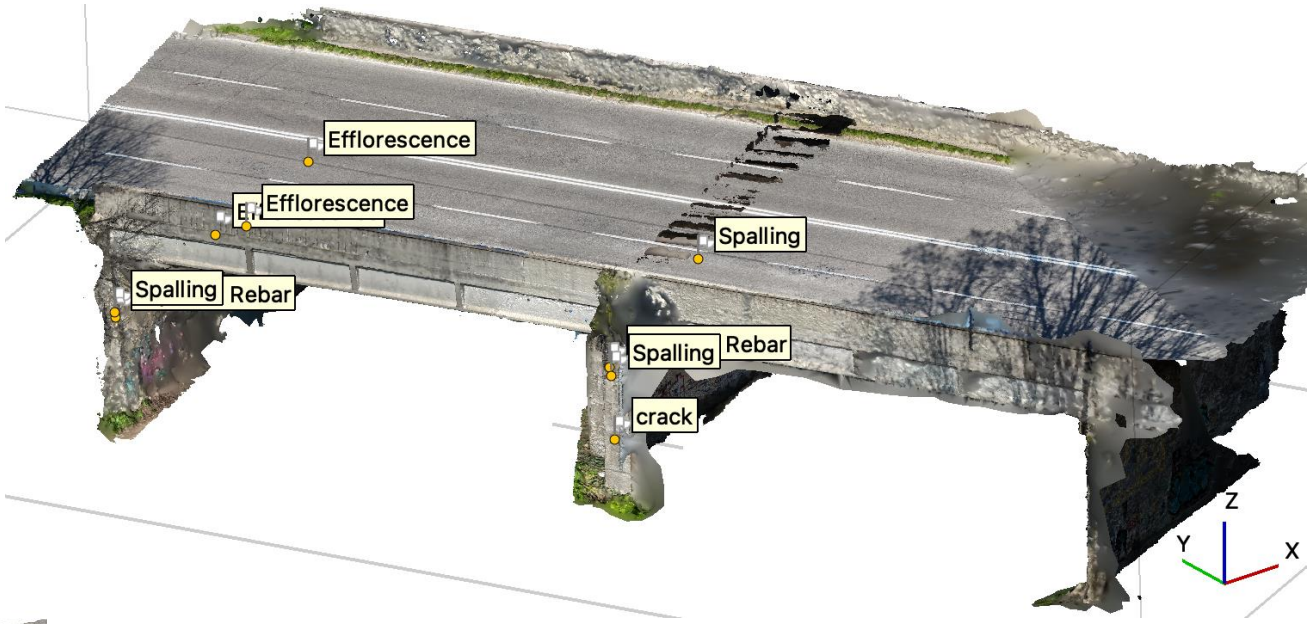
- **Unique Photogrammetry targets** printed at the **bounding box center** of defects
- **SIFT** feature matching across **overlapping images**
- Spatial position of defects is estimated using **matched image points** and Structure-from-Motion **(SfM)** geometry.





3D model generation using SfM Photogrammetry





Defects Localized on 3D Photogrammetry Meshed Model

Severity Assessment

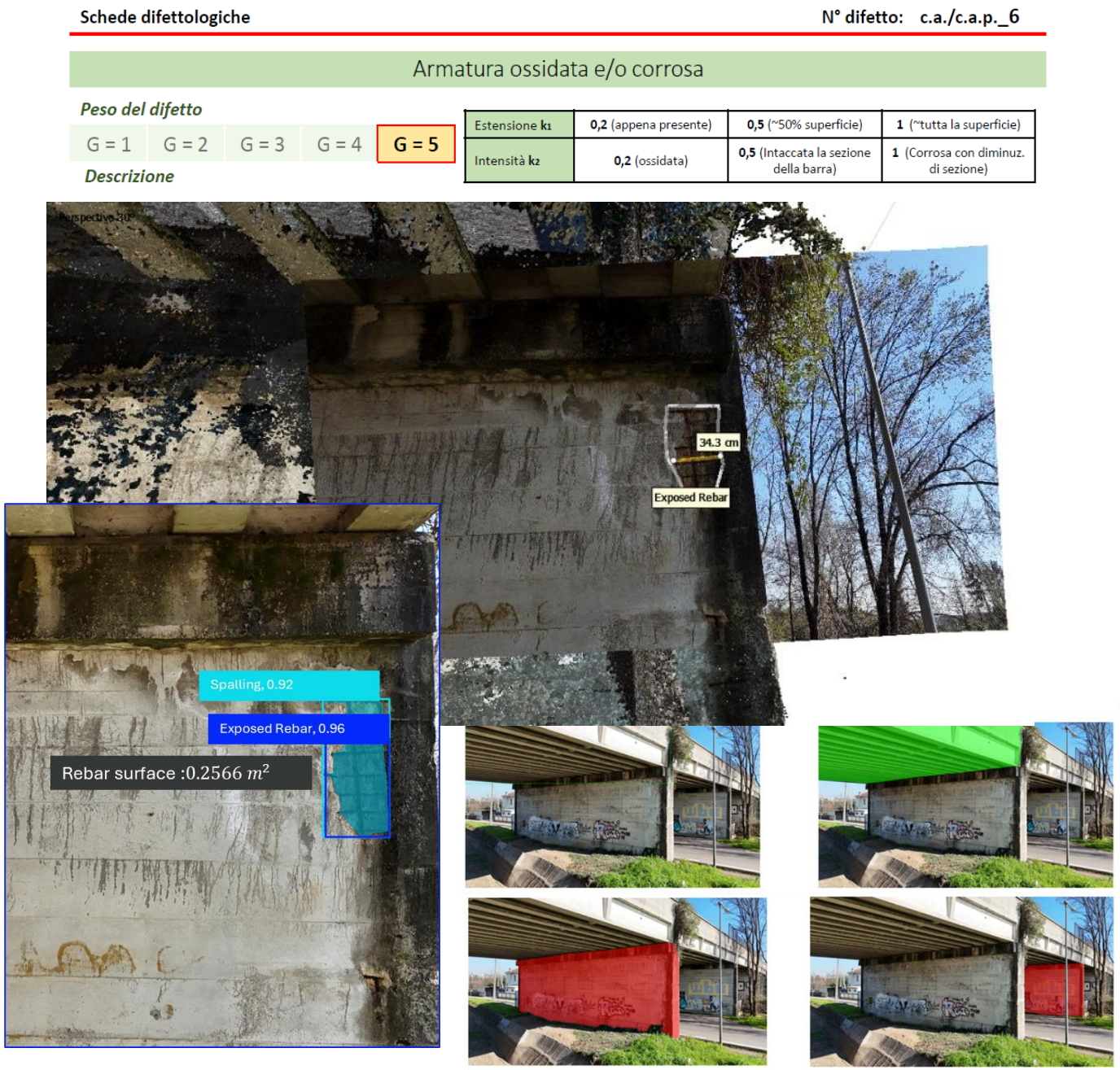
Defect indices assigned based on Italian Bridge Inspection Guidelines:

I. Detected defect (**assigned grade G**) mapped onto 3D-reconstructed model

II. **K1 (Extension)** and **K2 (Intensity)** computed in real-world scale in 3D model, integrating SAM2 in case of improvement.

Case Example: Exposed Rebar

- YOLO11 detection resulting → Severity Grade:
  - **G = 5**
- Real Coordinate measurement on 3D localized model
  - **defect length**: **34.3 cm**
- Severity Indexes:
  - **K1 = 0.2** → limited surface extension
  - **K2 = 0.2** → bar section affected



Comparison and Validation

- The system was evaluated **against Level 1 Visual Inspection forms** across four structural elements: **abutments, piers, beams,** and **deck**.

Level 1 Bridge Inspection Form													
1	Abutments Concrete												
Defect Description	Weight (G)	Traditional Inspection						Proposed Methodology					
		Extension K1			Intensity K2			Extension K1			Intensity K2		
		0.2	0.5	1	0.2	0.5	1	0.2	0.5	1	0.2	0.5	1
Moisture Stains (Efflorescence)	3		×				×	×					×
Spalling	2	×					×	×					×
Oxidized and/or corroded armor	5	×			×			×			×		
Horizontal Crack	2	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Vertical Crack	2	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Diagonal Crack	5	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP

Level 1 Bridge Inspection Form													
3	Pier Concrete												
Defect Description	Weight (G)	Traditional Inspection						Proposed Methodology					
		Extension K1			Intensity K2			Extension K1			Intensity K2		
		0.2	0.5	1	0.2	0.5	1	0.2	0.5	1	0.2	0.5	1
Moisture Stains (Efflorescence)	3		×			×			×				×
Spalling	2		×			×			×				×
Oxidized and/or corroded armor	5		×			×			×			×	
Horizontal Crack	2	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Vertical Crack	2		×			×		×			×		
Diagonal Crack	5	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP

Comparison and Validation

Key Observations:

- High consistency in identifying **efflorescence**, **spalling**, and **exposed rebar**.
- Detected additional defects **missed or underreported** in manual forms.
- The proposed method ensures **consistent severity assessment** by deriving K1 and K2 values **directly** from **real-world geometric measurements on the 3D model**, **reducing subjectivity** and inspector **variability**.

Level 1 Bridge Inspection Form														
14	Beams / Crossbeams Concrete													
Defect Description	Weight (G)	Traditional Inspection						Proposed Methodology						
		Extension K1			Intensity K2			Extension K1			Intensity K2			
		0.2	0.5	1	0.2	0.5	1	0.2	0.5	1	0.2	0.5	1	
Moisture Stains (Efflorescence)	3	×					×	×					×	
Spalling	2	×					×	×					×	
Oxidized and/or corroded armor	5	×			×				×			×		
Horizontal Crack	2	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	
Vertical Crack	2	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	
Diagonal Crack	5	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	

Level 1 Bridge Inspection Form														
18	Deck Concrete													
Defect Description	Weight (G)	Traditional Inspection						Proposed Methodology						
		Extension K1			Intensity K2			Extension K1			Intensity K2			
		0.2	0.5	1	0.2	0.5	1	0.2	0.5	1	0.2	0.5	1	
Moisture Stains (Efflorescence)	3	×					×		×				×	
Spalling	2		×				×		×				×	
Oxidized and/or corroded armor	5		×			×			×			×		
Horizontal Crack	2	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	
Vertical Crack	2	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	
Diagonal Crack	5	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	

Conclusion

Key Achievements:

- Developed a **semi-automated** bridge inspection workflow integrating **YOLO11**, **SAM2**, and **Structure-from-Motion** (SfM) for efficient, accurate, and scalable condition assessment.
- Enabled computation of **K1 (extension) and K2 (intensity)** indices in **real-world coordinates**, aligning with the **Italian National Bridge Inspection Guidelines**.
- **Enhanced classification consistency and objectivity**, reducing reliance on subjective human judgment during defect detection and evaluation.
- **Validated** the methodology through application on a **reinforced concrete overpass** in Lombardy, demonstrating its practical feasibility and strong agreement with traditional inspection outcomes.

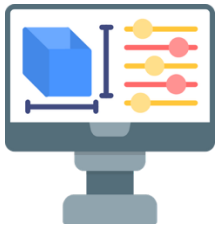
Limitation:

- Performance dependent on **image quality and environmental conditions**.
- Requires **extensive labeled training data** for model refinement.
- **Manual prompt refinement** occasionally needed for complex defects
- 3D reconstruction limited by **surface texture** and **image overlap requirements**.

Future Direction

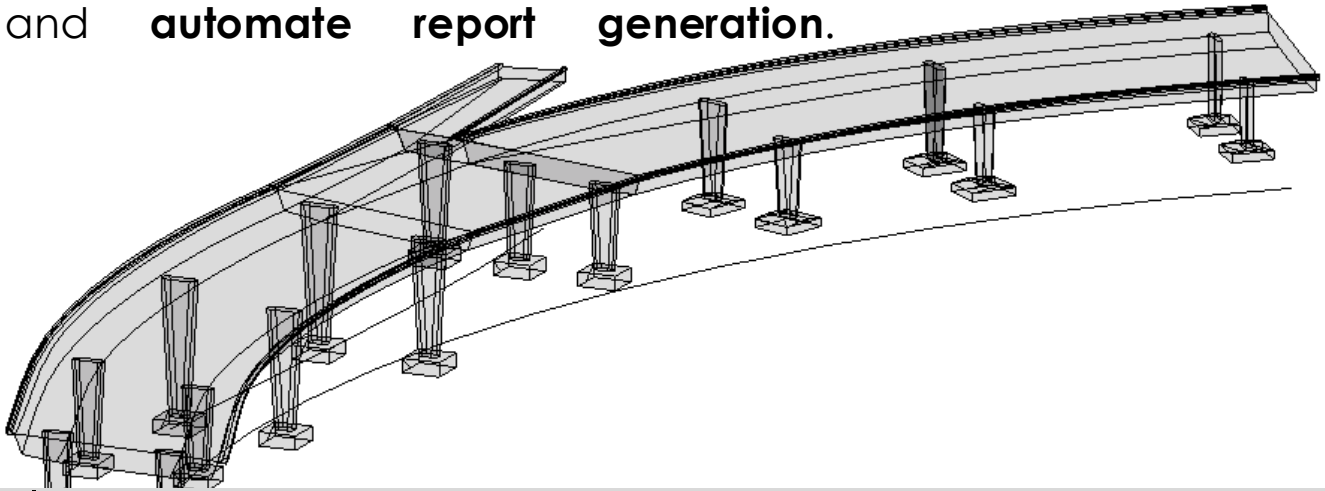
Efficient AI Models for Robust Detection:

- **Expand training datasets** with rare defects, varied materials, and weather conditions.
- **Improve YOLO11 generalization** across different bridge types and components.



Integration with Digital Twin Systems:

- Convert defect data into **BIM-compatible formats**
- Build interactive 3D models **for inspectors** to **review defects and updates** in **real time**.
- Enable **continuous health tracking** and **automate report generation**.



Thank you for your attention!