

Concrete Crack Detection and Segmentation

Authors

- **Yu-Sian Lin**

-  [yslin0114](#)

Department of Civil and Environmental Engineering, University of Illinois

- **Yueh-Ti Lee**

-  [Yueh-Ti](#)


Department of Civil and Environmental Engineering, University of Illinois

- **Minjiang Zhu**

-  [Minjiang-Zhu](#)

Department of Civil and Environmental Engineering, University of Illinois

- **Chengyou Yue**

-  [TensorYue](#)

Department of Civil and Environmental Engineering, University of Illinois

Introduction

The existence of cracks in concrete materials is of vital importance in Civil Engineering. An accurate and fast method to detect the existence of cracks in concrete images is always sought by engineers. Nowadays, even though a Convolutional neural network (CNN) based model can easily tell the existence of concrete cracks, the information of the exact locations of cracks is smeared in the network. We aim to firstly build a CNN-based model for crack detection, and then find and apply another model to locate the exact positions of cracks.

Please add brief introduction to U-Net.

We first train a CNN with the Surface Crack Detection dataset [1] to judge if any concrete crack exists. The dataset contains images (each has 227×227 pixels and RGB channels) of concrete surfaces with or without crack. Each class contains 20000 images. Examples are shown in Figure 1:

Negative



Positive



Figure 1: Negative and Positive Examples from the Surface Crack Detection Dataset

The dataset is splitted into a training set with ??? images and a testing set with ??? images.

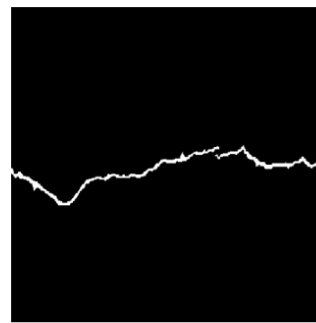
We then train a CNN-based network call U-Net [2] with the Concrete Crack Conglomerate Dataset [3] to segment the concrete from its cracks.

The dataset contains over 20000 crack images (each has 448×448 pixels and RGB channels). Each image data has an origin image and a mask image. Examples are shown in Figure ??:

Origin image



Mask image



Origin and Mask Images from the Concrete Crack Conglomerate Dataset

The dataset is splitted into a training set with 19801 images and a testing set with 2195 images.

Crack Detection

A Brief Introduction to CNN

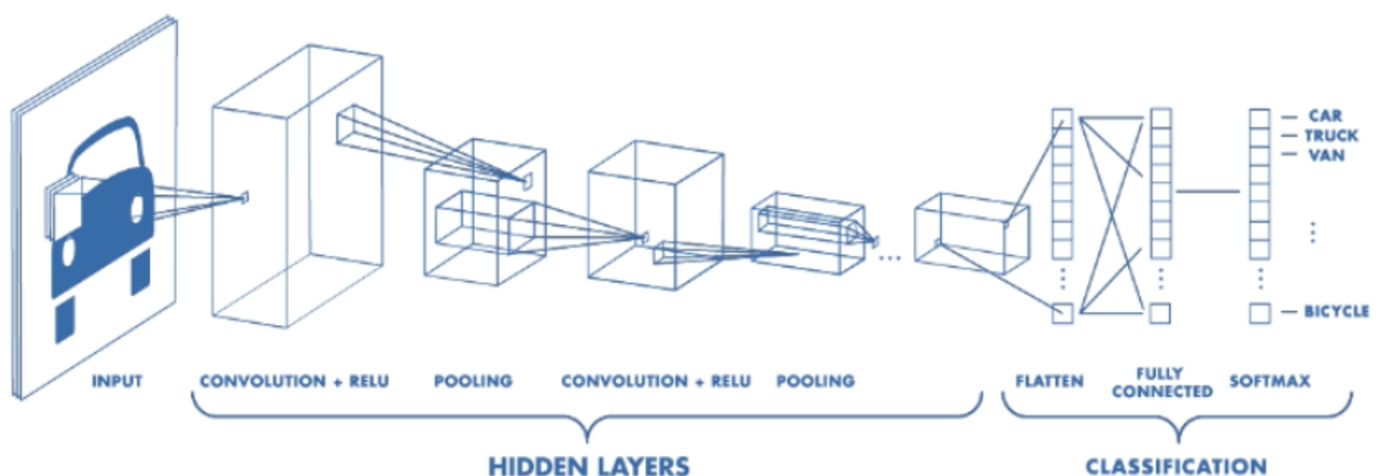


Figure 2: Basic Convolutional Neural Network for Classification.

CNN network is briefly introduced in this section. As shown in Figure 2, a typical CNN network involves several convolutional and pooling layers, and then several fully connected layers. Convolution is an operation that uses filter to extract information that we want to detect. The filter size determines how many filters will be applied to the input data. The kernel size determines the size of the area that the filters would apply to. Activation function is added to import nonlinearity into the model, considering the operation of filter is linear. MaxPooling is a down-sampling operation that allows our network to capture deeper information from its original dimensions. The pool size and strides determine the dimensions of the down-sample procedure. Notice that the sigmoid function (rather than the softmax function shown in Figure 2) will be applied in our model, as as we only have two classes of results.

Network Design

In the first convolutional block, we would specify 16 filters (consider 8 straight lines and 8 curves) with 3 by 3 kernels (consider the size of crack is relatively small), assign ReLu as the activation function in the Conv2D layer, and go deeper with a pool size of 2 by 2 in the MaxPool2D layer. In the second convolutional block, we double the channels number to 32 with Conv2D and apply the same MaxPool2D. Finally, we apply an GlobalAveragePooling2D layer, as we are focusing on the whole image rather than a part of it in segmentation. The coding form of this model is shown in Figure 3:

```
inputs = tf.keras.Input(shape=(120,120,3))
x = tf.keras.layers.Conv2D(filters=16, kernel_size=(3,3), activation='relu')(inputs)
x = tf.keras.layers.MaxPool2D(pool_size=(2,2))(x)
x = tf.keras.layers.Conv2D(filters=32, kernel_size=(3,3), activation='relu')(x)
x = tf.keras.layers.MaxPool2D(pool_size=(2,2))(x)

x = tf.keras.layers.GlobalAveragePooling2D()(x)
outputs = tf.keras.layers.Dense(1, activation='sigmoid')(x)
```

Figure 3: Model for Concrete Crack Classification using Keras

The result of our network would be a number in (0,1). We may treat it as the probability of the existence of crack in the image. Noticing that the original images have the size (227,227,3), we would resize it into (120,120,3) in the preprocessing procedure. The detailed properties of the network are listed in Figure 4 and Table ??.

Layer (type)	Output Shape	Param #
input_1 (InputLayer)	[(None, 120, 120, 3)]	0
conv2d (Conv2D)	(None, 118, 118, 16)	448
max_pooling2d (MaxPooling2D)	(None, 59, 59, 16)	0
conv2d_1 (Conv2D)	(None, 57, 57, 32)	4640
max_pooling2d_1 (MaxPooling2D)	(None, 28, 28, 32)	0
global_average_pooling2d (GlobalAveragePooling2D)	(None, 32)	0
dense (Dense)	(None, 1)	33
Total params: 5,121		
Trainable params: 5,121		
Non-trainable params: 0		

Figure 4: Model Summary and Hyperparameters

Table 1: Hyperparameters

Training	Validation	Testing	Optimizer	Loss Function	Metrics	Max Epochs
3360	840	1800	Adam	Binary Crossentropy	Accuracy	100

Results and Analysis

Below is the confusion matrix our model generated:

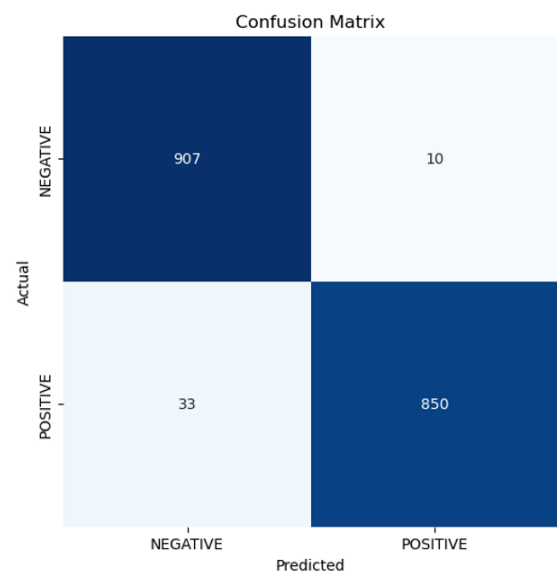


Figure 5: Confusion Matrix

and the loss during the training process:

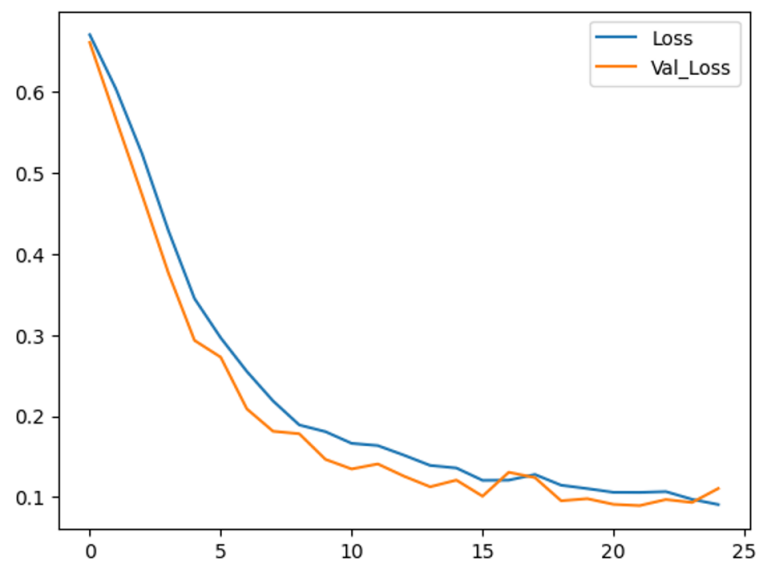


Figure 6: Loss Evolution

We can see that this trained model has good performance on the testing data. The training process only lasts for 25 epochs because of the early-stop procedure. We can further calculate the following parameters:

$$\begin{aligned}
\text{Precision} &= \frac{TP}{TP + FP} \\
\text{Recall} &= \frac{TP}{TP + FN} \\
\text{Score} &= 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \\
\text{MacroAvg} &= \frac{1}{n} \sum_{i=1}^n \text{Score}_i \\
\text{WeightedAvg} &= \frac{1}{n} \sum_{i=1}^n \text{Support}_i \times \text{Score}_i
\end{aligned} \tag{1}$$

Their specific values are shown in Table 2:

Table 2: Result Analysis

	Precision	Recall	Score	Support
Negative	0.96	0.99	0.98	917
Positive	0.99	0.96	0.97	883
Macro Avg	0.98	0.97	0.97	1800
Weighted Avg	0.97	0.97	0.97	1000

In short, the network has overall good performance.

Concrete Segmentation

U-Net is also CNN-based. The original U-Net architecture is shown below:

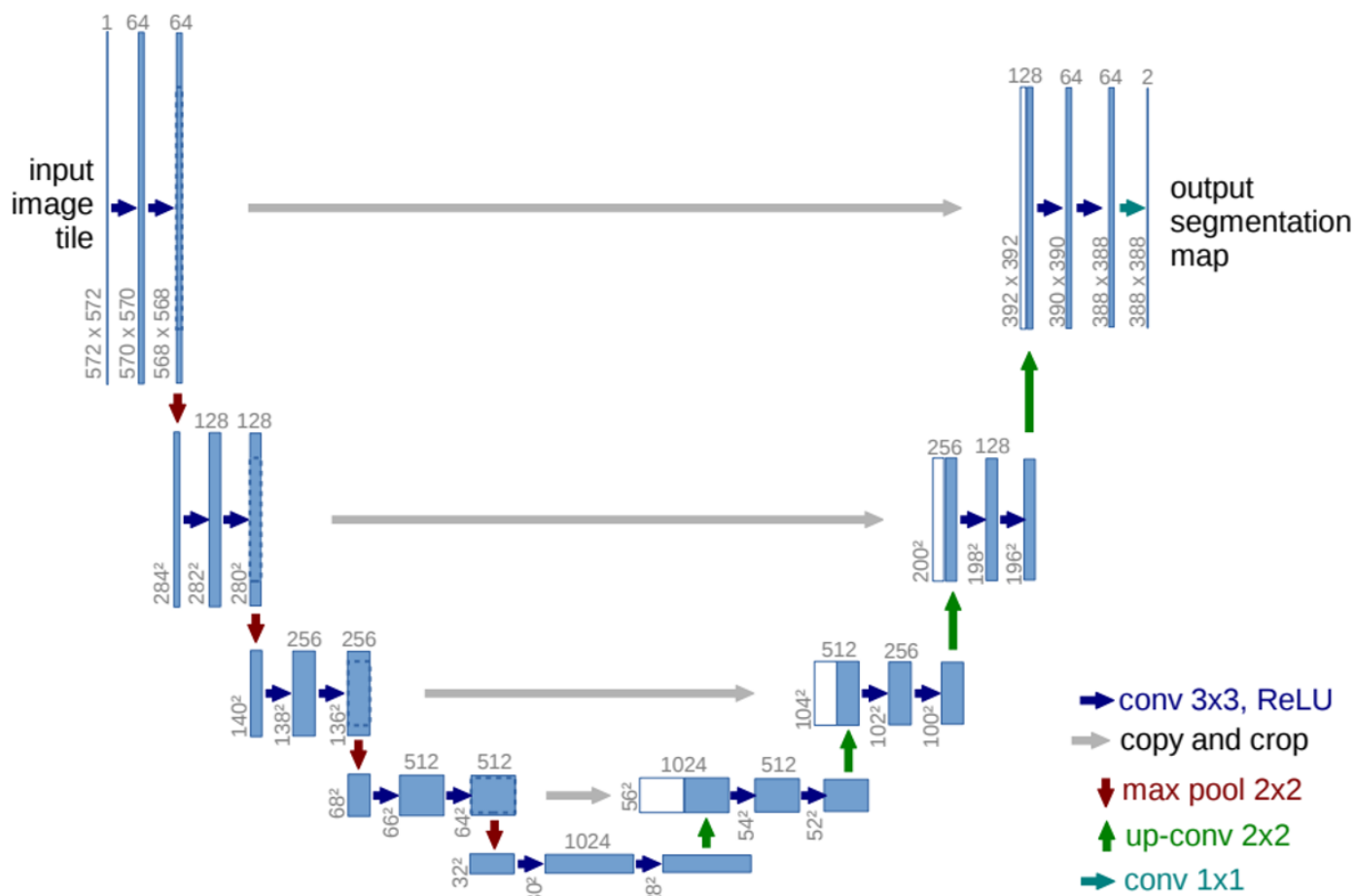


Figure 7: U-net Architecture.

Please add detailed description of U-Net in several sentences.

Modeling and Training

To achieve segmentation, we have built and trained two models, one based on our own architecture, and the other based on the paper. We perform a normalization before plugging in the U-Net architecture based on the range of RGB numbers, as shown in [8](#):

```
inputs = tf.keras.layers.Input((IMG_HEIGHT, IMG_WIDTH, IMG_CHANNELS))
s = tf.keras.layers.Lambda(lambda x: x / 255)(inputs)
```

Figure 8: Input Normalization

In the previous classification model, we have shown that the first convolutional block only needs 16 filters to perform well. We also add a random dropout in each convolution block to prevent the overfitting problem. Based on this experiment, we modified U-Net architecture as shown in [9](#):

```

# Downsampling
c1 = tf.keras.layers.Conv2D(16, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(s)
c1 = tf.keras.layers.Dropout(0.1)(c1)
c1 = tf.keras.layers.Conv2D(16, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(c1)
p1 = tf.keras.layers.MaxPooling2D((2,2))(c1)

c2 = tf.keras.layers.Conv2D(32, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(p1)
c2 = tf.keras.layers.Dropout(0.1)(c2)
c2 = tf.keras.layers.Conv2D(32, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(c2)
p2 = tf.keras.layers.MaxPooling2D((2,2))(c2)

c3 = tf.keras.layers.Conv2D(64, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(p2)
c3 = tf.keras.layers.Dropout(0.2)(c3)
c3 = tf.keras.layers.Conv2D(64, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(c3)
p3 = tf.keras.layers.MaxPooling2D((2,2))(c3)

c4 = tf.keras.layers.Conv2D(128, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(p3)
c4 = tf.keras.layers.Conv2D(128, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(c4)
c4 = tf.keras.layers.Dropout(0.2)(c4)
p4 = tf.keras.layers.MaxPooling2D((2,2))(c4)

c5 = tf.keras.layers.Conv2D(256, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(p4)
c5 = tf.keras.layers.Dropout(0.3)(c5)
c5 = tf.keras.layers.Conv2D(256, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(c5)

# Upsampling
u6 = tf.keras.layers.Conv2DTranspose(128, (2,2), strides=(2,2), padding='same')(c5)
u6 = tf.keras.layers.concatenate([u6, c4])
c6 = tf.keras.layers.Conv2D(128, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(u6)
c6 = tf.keras.layers.Dropout(0.2)(c6)
c6 = tf.keras.layers.Conv2D(128, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(c6)

u7 = tf.keras.layers.Conv2DTranspose(64, (2,2), strides=(2,2), padding='same')(c6)
u7 = tf.keras.layers.concatenate([u7, c3])
c7 = tf.keras.layers.Conv2D(64, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(u7)
c7 = tf.keras.layers.Dropout(0.2)(c7)
c7 = tf.keras.layers.Conv2D(64, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(c7)

u8 = tf.keras.layers.Conv2DTranspose(32, (2,2), strides=(2,2), padding='same')(c7)
u8 = tf.keras.layers.concatenate([u8, c2])
c8 = tf.keras.layers.Conv2D(32, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(u8)
c8 = tf.keras.layers.Dropout(0.1)(c8)
c8 = tf.keras.layers.Conv2D(32, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(c8)

u9 = tf.keras.layers.Conv2DTranspose(16, (2,2), strides=(2,2), padding='same')(c8)
u9 = tf.keras.layers.concatenate([u9, c1])
c9 = tf.keras.layers.Conv2D(16, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(u9)
c9 = tf.keras.layers.Dropout(0.1)(c9)
c9 = tf.keras.layers.Conv2D(16, (3,3), activation='relu', kernel_initializer='he_normal', padding='same')(c9)

# Output
outputs = tf.keras.layers.Conv2D(1,(1,1), activation='sigmoid')(c9)

```

Figure 9: Modified U-Net Architecture

The original images have the size (448,448,3). We would keep this size for this network, but there is still a resizing procedure that allows this network to predict images with different sizes. The detailed architecture of this model is summarized in [Figure 10](#):

Layer (type)	Output Shape	Param #	Connected to			
=====						
input_2 (InputLayer)	(None, 448, 448, 3)	0	[]			
lambda_1 (Lambda)	(None, 448, 448, 3)	0	['input_2[0][0]']	concatenate_4 (Concatenate)	(None, 56, 56, 256)	0
conv2d_19 (Conv2D)	(None, 448, 448, 16)	448	['lambda_1[0][0]']			
dropout_9 (Dropout)	(None, 448, 448, 16)	0	['conv2d_19[0][0]']	conv2d_29 (Conv2D)	(None, 56, 56, 128)	295040
conv2d_20 (Conv2D)	(None, 448, 448, 16)	2320	['dropout_9[0][0]']	dropout_14 (Dropout)	(None, 56, 56, 128)	0
max_pooling2d_4 (MaxPooling2D)	(None, 224, 224, 16)	0	['conv2d_20[0][0]']	conv2d_30 (Conv2D)	(None, 56, 56, 128)	147584
conv2d_21 (Conv2D)	(None, 224, 224, 32)	4640	['max_pooling2d_4[0][0]']	conv2d_transpose_5 (Conv2DTran	(None, 112, 112, 64)	32832
dropout_10 (Dropout)	(None, 224, 224, 32)	0	['conv2d_21[0][0]']	spose)		
conv2d_22 (Conv2D)	(None, 224, 224, 32)	9248	['dropout_10[0][0]']	concatenate_5 (Concatenate)	(None, 112, 112, 12)	0
max_pooling2d_5 (MaxPooling2D)	(None, 112, 112, 32)	0	['conv2d_22[0][0]']			
conv2d_23 (Conv2D)	(None, 112, 112, 64)	18496	['max_pooling2d_5[0][0]']	conv2d_31 (Conv2D)	(None, 112, 112, 64)	73792
dropout_11 (Dropout)	(None, 112, 112, 64)	0	['conv2d_23[0][0]']			
conv2d_24 (Conv2D)	(None, 112, 112, 64)	36928	['dropout_11[0][0]']	dropout_15 (Dropout)	(None, 112, 112, 64)	0
max_pooling2d_6 (MaxPooling2D)	(None, 56, 56, 64)	0	['conv2d_24[0][0]']	conv2d_32 (Conv2D)	(None, 112, 112, 64)	36928
conv2d_25 (Conv2D)	(None, 56, 56, 128)	73856	['max_pooling2d_6[0][0]']			
conv2d_26 (Conv2D)	(None, 56, 56, 128)	147584	['conv2d_25[0][0]']	conv2d_transpose_6 (Conv2DTran	(None, 224, 224, 32)	8224
dropout_12 (Dropout)	(None, 56, 56, 128)	0	['conv2d_26[0][0]']	spose)		
max_pooling2d_7 (MaxPooling2D)	(None, 28, 28, 128)	0	['dropout_12[0][0]']	concatenate_6 (Concatenate)	(None, 224, 224, 64)	0
conv2d_27 (Conv2D)	(None, 28, 28, 256)	295168	['max_pooling2d_7[0][0]']			
dropout_13 (Dropout)	(None, 28, 28, 256)	0	['conv2d_27[0][0]']	conv2d_33 (Conv2D)	(None, 224, 224, 32)	18464
conv2d_28 (Conv2D)	(None, 28, 28, 256)	590080	['dropout_13[0][0]']			
conv2d_transpose_4 (Conv2DTran	(None, 56, 56, 128)	131200	['conv2d_28[0][0]']	dropout_16 (Dropout)	(None, 224, 224, 32)	0
spose)				conv2d_34 (Conv2D)	(None, 224, 224, 32)	9248
				conv2d_transpose_7 (Conv2DTran	(None, 448, 448, 16)	2064
				spose)		
				concatenate_7 (Concatenate)	(None, 448, 448, 32)	0
				conv2d_35 (Conv2D)	(None, 448, 448, 16)	4624
				dropout_17 (Dropout)	(None, 448, 448, 16)	0
				conv2d_36 (Conv2D)	(None, 448, 448, 16)	2320
				conv2d_37 (Conv2D)	(None, 448, 448, 1)	17
				=====		
				Total params: 1,941,105		
				Trainable params: 1,941,105		
				Non-trainable params: 0		

Figure 10: Model Summary

Other properties of this network is listed in Table 3:

Table 3: U-Net Hyperparameters.

Training	Validation	Testing	Optimizer	Loss Function	Metrics	Epochs
105	2	17	Adam	Binary Crossentropy	Accuracy	50

U-Net still learns well even the training dataset is small.

So how small it is? Describe your training dataset.

The training and testing losses are plotted in Figure 11:

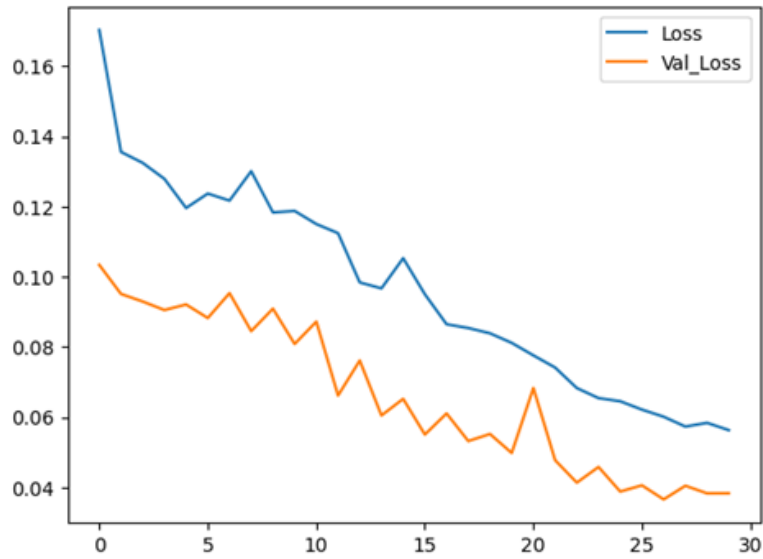


Figure 11: U-Net Loss Evaluation.

We can see that this trained model has good performance on the testing data. It only takes 30 epochs because of the early-stop procedure.

Results and Analysis

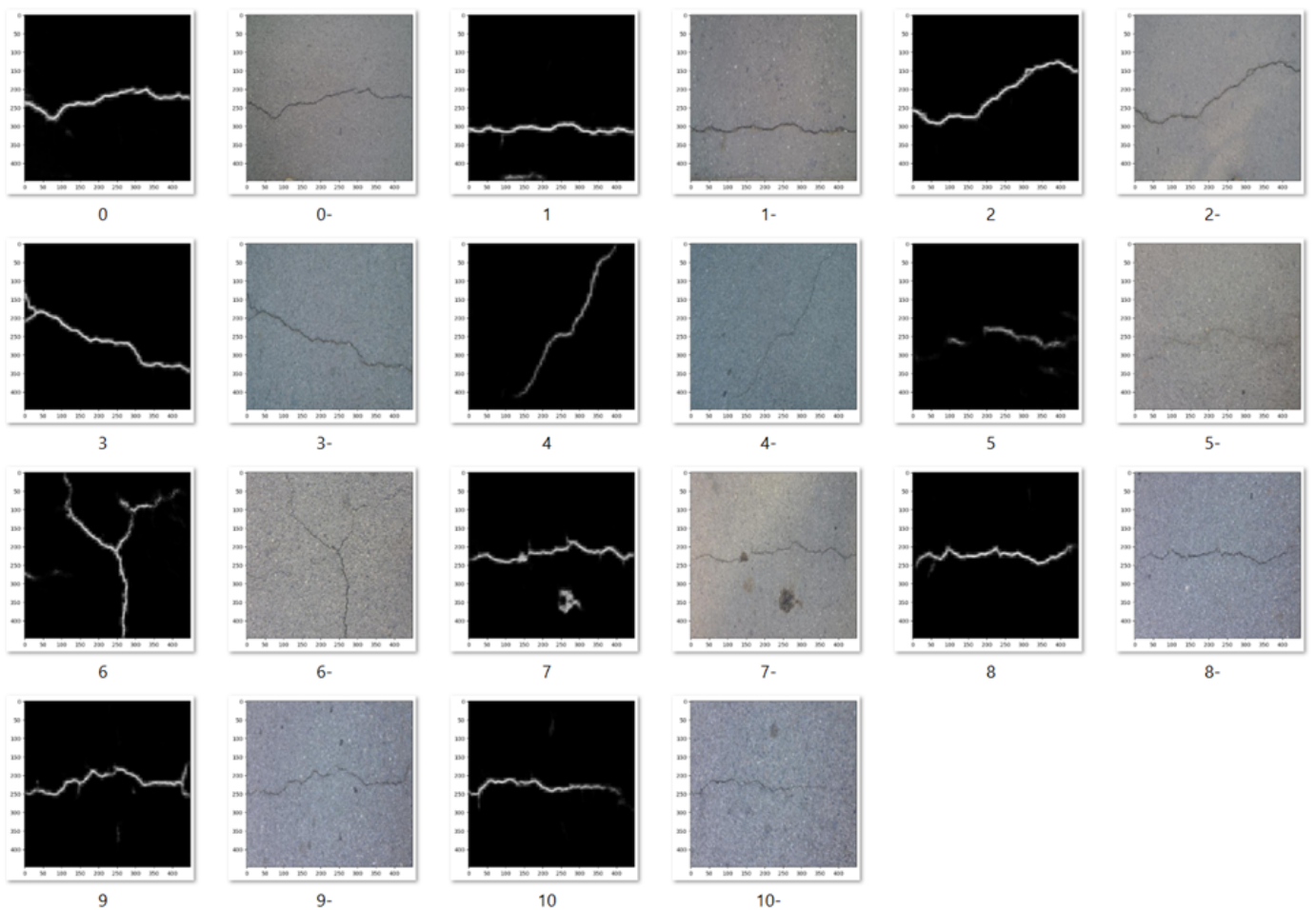


Figure 12: Prediction Result

The prediction results of our testing images is shown in [12](#). It performs well. However, we can also notice that in the testing image 7, the network recognizes the dark-colored zone as a crack.

We are still working on the next U-Net model with Conv2D=>BatchNormalization=>ReLU as conv_block. We also trained a U-Net model with pretrained Inception as backbone, but we haven't upload it yet.

Computer vision-based concrete crack detection using U-net fully convolutional networks [4]

Performance Evaluation of Deep CNN-Based Crack Detection and Localization Techniques for Concrete Structures [5]

1. **Surface Crack Detection** <https://www.kaggle.com/datasets/arunrk7/surface-crack-detection>
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Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015 (2015)
<https://doi.org/gcggk7j>
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3. **Concrete Crack Conglomerate Dataset**
Eric Bianchi, Matthew Hebdon
University Libraries, Virginia Tech (2021) <https://doi.org/gq9q35>
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4. **Computer vision-based concrete crack detection using U-net fully convolutional networks**
Zhenqing Liu, Yiwen Cao, Yize Wang, Wei Wang
Automation in Construction (2019-08) <https://doi.org/gghznx>
DOI: [10.1016/j.autcon.2019.04.005](https://doi.org/10.1016/j.autcon.2019.04.005)
5. **Performance Evaluation of Deep CNN-Based Crack Detection and Localization Techniques for Concrete Structures**
Luqman Ali, Fady Alnajjar, Hamad Al Jassmi, Munkhjargal Gocho, Wasif Khan, MAdel Serhani
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