

INTISARI

Selama beberapa dekade terakhir, cukup banyak jembatan bentang panjang telah dibangun atau masih dalam tahap konstruksi di Indonesia. Jembatan tersebut umumnya menggunakan jenis jembatan *cable-stayed* yang merupakan tipe paling cocok untuk jembatan dengan bentang-medium hingga bentang-panjang dengan bentang utamanya berkisar antara 200 m–1000 m. Masa konstruksi jembatan *cable-stayed* di Indonesia, yang sebagian besar wilayahnya rawan gempa, memakan waktu rata-rata 3 tahun atau bahkan lebih. Pada rentang waktu tersebut sangat mungkin bagi jembatan *cable-stayed* mengalami peristiwa gempa.

Penelitian ini bertujuan untuk menyelidiki respon dinamik jembatan *cable-stayed* pada masa konstruksi dengan mempertimbangkan pengaruh berbagai sudut datang gempa. Selain itu dikaji juga apakah jembatan pada masa konstruksi yang mengalami eksitasi gempa memberikan respon dinamik lebih *critical* daripada jembatan yang sudah tersambung. Kajian eksperimental menggunakan *shaking-table* merupakan kajian utama pada penelitian ini. Model jembatan dibuat dengan mengikuti hukum similaritas untuk pengujian dinamik dengan skala geometri sebesar 160. Adapun variasi besarnya sudut arah gempa ditetapkan 0° , 45° , dan 90° terhadap sumbu longitudinal jembatan. Input gempa menggunakan catatan gempa Kobe yang diperoleh dari PEER *Strong Motion Database*. Kajian numerik dilakukan dengan *time history analysis* menggunakan *software* Midas/Civil. Selain respon terhadap gaya kabel jembatan, respon dinamik yang ditinjau dalam studi ini adalah respon percepatan dan perpindahan pada: pilon bagian atas, girder tengah, ujung girder bentang utama, dan ujung girder bentang samping.

Hasil analisis respon *free vibration* dari kajian eksperimental dengan melakukan *impact test* diketahui bahwa frekuensi natural fundamental dan rasio redaman model terskala jembatan Suramadu bentang separuh masing-masing adalah 0,723 Hz (arah longitudinal) dan 0,05. Berdasarkan kajian eksperimental menggunakan *shaking-table* terhadap model terskala jembatan Suramadu bentang separuh akibat eksitasi gempa arah 0° , arah 45° , dan arah 90° terhadap sumbu longitudinal jembatan diketahui bahwa: (a) Faktor amplifikasi percepatan maksimum pada puncak pilon sesuai arah eksitasi, berturut-turut adalah: 0,769, 1,684, dan 1,925. Faktor amplifikasi percepatan maksimum terbesar terjadi pada arah eksitasi gempa 90° terhadap sumbu longitudinal jembatan; (b) Faktor amplifikasi percepatan maksimum pada girder jembatan bagian tengah berturut-turut adalah: 0,218, 0,653, dan 1,061. Faktor amplifikasi terbesar terjadi akibat eksitasi gempa arah 90° terhadap sumbu longitudinal jembatan; (c) Faktor amplifikasi percepatan maksimum pada girder jembatan bagian ujung berturut-turut adalah: 0,581, 0,516, dan 0,811. Faktor amplifikasi percepatan maksimum terbesar terjadi akibat eksitasi gempa arah 90° terhadap sumbu longitudinal jembatan; (d) Faktor amplifikasi respon dinamik gaya kabel maksimum berturut-turut adalah: 1,173, 1,022, dan 1,022 dan faktor amplifikasi terbesar disebabkan oleh eksitasi gempa searah sumbu longitudinal jembatan; (e) Perpindahan maksimum pada girder jembatan bagian ujung berturut-turut adalah: 0,462 mm, 0,546 mm, dan 0,867 mm, dan respon perpindahan yang terjadi masih dibawah toleransi yaitu 3 mm ($L/400$).

Kajian numerik terhadap model terskala jembatan bentang separuh akibat eksitasi gempa arah 0° , arah 45° , dan arah 90° terhadap sumbu longitudinal jembatan menghasilkan kecenderungan yang sama, yaitu: (a) Faktor amplifikasi percepatan maksimum terbesar pada puncak pilon terjadi akibat eksitasi gempa 90° terhadap sumbu longitudinal jembatan, dengan faktor amplifikasi percepatan maksimum, berturut-turut adalah: 0,817, 3,338, dan 4,658; (b) Faktor amplifikasi percepatan maksimum terbesar pada girder bagian tengah terjadi akibat eksitasi gempa 90° terhadap sumbu longitudinal jembatan, dengan respon percepatan umumnya lebih kecil dari input percepatan gempa, yaitu: 0,071, 0,706, dan 0,997; (c) Faktor amplifikasi percepatan maksimum terbesar pada girder jembatan bagian ujung bentang terjadi akibat eksitasi gempa 90° terhadap sumbu longitudinal jembatan, dengan faktor amplifikasi percepatan maksimum berturut-turut adalah: 0,629, 2,311, dan 3,186; (d) Faktor amplifikasi respon dinamik gaya kabel maksimum terbesar disebabkan oleh eksitasi gempa 90° terhadap sumbu longitudinal jembatan, dengan faktor amplifikasi berturut-turut adalah: 1,097, 1,211, dan 1,214; (e) Perpindahan maksimum pada girder jembatan bagian ujung berturut-turut adalah: 0,975 mm; 0,733 mm; dan 0,500 mm, dan respon perpindahan yang terjadi masih dibawah toleransi yaitu 3 mm ($L/400$).

Berdasarkan kajian numerik terhadap model terskala jembatan bentang utuh akibat eksitasi gempa arah 0° , arah 45° , dan arah 90° terhadap sumbu longitudinal jembatan diketahui bahwa: (a) Faktor amplifikasi percepatan maksimum terbesar pada puncak pilon terjadi akibat eksitasi gempa 90° terhadap sumbu longitudinal jembatan, dengan faktor amplifikasi 2,440. Nilai tersebut jauh lebih kecil dari faktor amplifikasi pada kondisi jembatan bentang separuh, yaitu 4,658; (b) Faktor amplifikasi percepatan maksimum terbesar pada girder jembatan bagian tengah terjadi akibat eksitasi gempa 90° terhadap sumbu longitudinal jembatan, dengan faktor amplifikasi 1. Nilai tersebut mendekati sama dengan faktor amplifikasi pada kondisi jembatan bentang separuh, yaitu 0,997; (c) Faktor amplifikasi respon dinamik gaya kabel maksimum terbesar terjadi akibat eksitasi gempa 0° terhadap sumbu longitudinal jembatan, dengan faktor amplifikasi 1,514. Nilai tersebut lebih tinggi dari faktor amplifikasi pada kondisi jembatan bentang separuh, yaitu 1,214.

Berdasarkan hasil kajian eksperimental maupun numerik terhadap model terskala jembatan Suramadu, dapat diketahui bahwa: (a) Jembatan bentang separuh menghasilkan faktor amplifikasi percepatan maksimum terbesar pada ujung girder, akibat eksitasi gempa 90° terhadap sumbu longitudinal jembatan, dengan nilai yang mendekati sama dengan kondisi pada saat jembatan bentang utuh, yaitu 3,186; (b) Jembatan bentang separuh menghasilkan faktor amplifikasi dinamik gaya kabel maksimum terbesar akibat eksitasi gempa searah sumbu longitudinal jembatan, dengan nilai yang lebih kecil (sekitar 20%) dari faktor amplifikasi kondisi jembatan bentang utuh, yaitu 1,514; (c) Jembatan bentang separuh menghasilkan perpindahan arah transversal yang cukup besar di ujung-ujung bebas girder, yang kondisi ini tidak dijumpai pada jembatan utuh; (d) Secara umum, respon percepatan maksimum dalam arah transversal pada puncak pilon maupun girder cenderung meningkat dengan bertambahnya sudut arah eksitasi gempa, sedangkan respon percepatan maksimum dalam arah longitudinal cenderung berkurang dengan semakin besarnya sudut arah eksitasi gempa. Kondisi jembatan *cable-stayed* saat

masa konstruksi perlu ditinjau perilaku struktural dan stabilitasnya terhadap beban gempa dalam proses perancangan detail struktur (*Detail Engineering Design*), utamanya apabila dibangun pada wilayah rawan gempa.

Kata kunci: respon dinamik, masa konstruksi, *shaking-table test*, jembatan *cabl-stayed*, eksitasi gempa, masa konstruksi

ABSTRACT

Over the last few decades, quite a number of long-span bridges have been built or are still under construction in Indonesia. The bridges generally use a type of cable-stayed bridge which is the most suitable type for medium-to-long-span bridges with a main span ranging from 200 m-1000 m. The period of cable-stayed bridge construction in Indonesia, where most of the area is prone to earthquakes, takes an average of 3 years or even more. During this time, it is very possible for cable-stayed bridges to experience earthquake events.

This study aims to investigate the dynamic response of a cable-stayed bridge during construction by considering the effects of the earthquake angle direction. In addition, it was also examined whether the bridge during construction that experienced earthquake excitation provided a dynamic response more critical than the bridge that had been completed. The experimental study using shaking-table was the primary study in this research. The bridge model was made by following the law of similarity for dynamic testing with geometry scale 160. The magnitude of the earthquake angle direction was set to 0° , 45° , and 90° relative to the longitudinal axis of the bridge. The earthquake input force used the Kobe earthquake record obtained from PEER Strong Motion Database. Numerical studies were performed with time history analysis using Midas/Civil software for various earthquake angles. In addition to the response of the bridge cable force, the dynamic response observed in this study was the acceleration and displacement response at the top pylon, the center girder, the end of the main span girder, and the end of the side span girder.

The results of the analysis of free vibration response from experimental studies by doing an impact test revealed that the fundamental natural frequency and the damping ratio of the scaled model of the half-span Suramadu bridge were 0,723 Hz (longitudinal direction) and 0,05 respectively. Based on experimental studies using shaking-table on the scaled model of the half-span Suramadu bridge due to earthquake excitation in the direction of 0° , 45° , and 90° relative to the longitudinal axis of the bridge, it was known that: (a) The maximum acceleration amplification factors at the top of the pylon in the direction of earthquake excitation were respectively: 0,769, 1,684, and 1,925. The largest maximum acceleration amplification factor due to earthquake excitation in the direction of 90° relative to the longitudinal axis of the bridge; (b) The maximum acceleration amplification factors at the center of the girder were respectively: 0,218, 0,653, and 1,061. The largest amplification factor occurring due to the earthquake excitation in the direction of the 90° relative to the longitudinal axis of the bridge; (c) The maximum acceleration amplification factors at the free end of the girder were respectively: 0,581, 0,516 and 0,811. The largest maximum amplification factor occurring due to the earthquake excitation in the direction of 90° relative to the longitudinal axis of the bridge; (d) The amplification factors of the dynamic response of the maximum stayed-cable force were respectively: 1,173, 1,022, and 1,022, and the largest amplification factor was caused by the earthquake excitation in the direction of the longitudinal axis of the bridge; (e) The maximum displacements of the free end of

the girder bridge were respectively: 0,462 mm, 0,546 mm and 0,867 mm, and the displacement response were less than the allowable 3 mm of $L/400$.

The numerical studies on the scaled model of the half-span Suramadu bridge due to earthquake excitation in the direction of 0° , 45° , and 90° relative to the longitudinal axis of the bridge, produce the same tendency, i.e.: (a) The largest maximum acceleration amplification factors at the top of the pylon occurred due to earthquake excitation in the direction of 90° relative to the longitudinal axis of the bridge, with the maximum acceleration amplification factors were respectively: 0,817, 3,338, and 4,658; (b) The largest maximum acceleration amplification factors at the center of the girder occurred due to the earthquake excitation in the direction of 90° relative to the longitudinal axis of the bridge, with the acceleration response generally smaller than the earthquake acceleration input, it were respectively: 0,071, 0,706, and 0,997; (c) The largest maximum acceleration amplification factors at the free end of the girder occurred due to the earthquake excitation in the direction of 90° relative to the longitudinal axis of the bridge, with the maximum acceleration amplification factors were respectively: 0,629, 2,311, and 3,186; (d) The amplification factor of the dynamic response of the largest maximum stayed-cable force was caused by the earthquake excitation in the direction of 90° relative to the longitudinal axis of the bridge, with amplification factors were respectively: 1,097, 1,211 and 1,214; (e) The maximum displacements at the free end of the girder were respectively: 0,975 mm; 0,733 mm; and 0,500 mm, and the displacements response were less than the allowable 3 mm of $L/400$.

Based on the numerical studies on the scaled model of the full-span Suramadu bridge due to earthquake excitation in the direction of the 0° , 45° , and 90° relative to the longitudinal axis of the bridge, it were known that: (a) The largest maximum acceleration amplification factor at the top of the pylon occurred due to the earthquake excitation in the direction of 90° relative to the longitudinal axis of the bridge, with an amplification factor of 2,440. This value was much smaller than the amplification factor in the condition of the half-span bridge, which is 4,658; (b) The largest maximum acceleration amplification factor at the center of the girder occurred due to the earthquake excitation in the direction of 90° relative to the longitudinal axis of the bridge, with an amplification factor of 1. This value was close to the same as the amplification factor in the condition of the half-span bridge, which is 0,997; (c) The amplification factor of the dynamic response of the largest maximum stayed-cable force occurred due to the earthquake excitation in the direction of the longitudinal axis of the bridge, with an amplification factor of 1,514. This value was higher than the amplification factor in the condition of the half-span bridge, which is 1,214.

Based on the results of experimental and numerical studies of the scaled model of Suramadu bridge, it can be seen that: (a) The half-span bridge produced the largest maximum acceleration factor at the free end of the girder, caused by the earthquake excitation in the direction of 90° relative to the longitudinal axis of the bridge, with a value that was close to the same as the condition at the full-span bridge, which is 3,186; (b) The half-span bridge produced the largest amplification factor of the dynamic response of the maximum stayed-cable force caused by the earthquake excitation in the direction of the longitudinal axis of the bridge, with a

smaller value (around 20%) from the amplification factor of the full-span bridge, which is 1,514; (c) The half-span bridge produced a quite large transverse direction of displacement at the free ends of the girder, which is not found on the full-span bridge; (d) In general, the maximum acceleration response in the transversal direction at the top of the pylon and the girder tends to increase with increasing the angles of the earthquake excitation, while the maximum acceleration response in the longitudinal direction tends to decrease with the greater angles of the earthquake excitation. The condition of the cable-stayed bridge during construction period needs to be reviewed for structural behavior and its stability due to earthquake loads in the detailed engineering design process, especially if it is built in earthquake-prone areas.

Keywords: dynamic responses, shaking table test, cable-stayed bridge, earthquake excitation, and during construction