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NONLINEAR BEHAVIOUR OF A REINFORCED CONCRETE FRAME IN BANJA LUKA FOR SITE-SPECIFIC SEISMICITY AND SOIL CONDITIONS

Abstract:

This study presents a seismic capacity assessment of a reinforced concrete structure in central Banja Luka, Bosnia and Herzegovina, using nonlinear dynamic analysis in OpenSees under Python environment. Site-specific soil conditions, characterized by dynamic amplification factors of approximately 1.2, are incorporated into the analysis. Structural response is evaluated under the recorded 1981 Banja Luka earthquake and Eurocode 8 spectrum-compatible artificial accelerograms for soil types A through E, considering an RC frame structure of importance class IV with reference rock acceleration of 0.15g. Results reveal that frequency content differences between the recorded earthquake and code spectra may significantly influence structural response, particularly for intermediate-period structures. The analysis demonstrates that deep geological effects cannot always be adequately captured by general Eurocode 8 provisions. The study provides insights into seismic performance of a representative building typology and evidence-based recommendations for enhanced design practice in regions with moderate seismicity and complex geological conditions.

Keywords: non-linear analysis, frame structure, seismic demand, numerical modeling, Eurocode 8, OpenSees

НЕЛИНЕАРНО ПОНАШАЊЕ АРМИРАНОБЕТОНСКОГ РАМА У БАЊА ЛУЦИ ЗА ЛОКАЛНО СПЕЦИФИЧНУ СЕИЗМИЧНОСТ И УСЛОВЕ ТЛА

Сажетак:

Ова студија представља процену сеизмичког капацитета армирано-бетонске конструкције у централном делу Бање Луке применом нелинеарне динамичке анализе у OpenSees окружењу у Python интерфејсу. Локални услови тла, карактерисани факторима динамичке амплификације од приближно 1.2, експлицитно су укључени у анализу. Одговор конструкције процењује се под дејством регистрованог земљотреса из 1981. године и синтетичких акцелерограма компатибилних са спектром према Еврокоду 8 за типове тла од А до Е, за рамовску конструкцију класе важности IV и референтног убрзања стене 0.15g. Резултати показују да разлике у фреквентном садржају између регистрованог земљотреса и спектра из прописа могу значајно утицати на сеизмички одговор, нарочито код конструкција средњих периода. Анализа показује да дубински геолошки ефекти не могу увек бити адекватно обухваћени општим одредбама Еврокода 8. Студија пружа увиде у сеизмичко понашање репрезентативне типологије објеката и препоруке за унапређење пројектантске праксе у регионима умерене сеизмичности и комплексних геолошких услова.

Кључне речи: нелинеарна анализа, рамовска конструкција, сеизмички захтев, нумеричко моделирање, Еврокод 8, OpenSees

1. INTRODUCTION

The Banja Luka region has experienced repeated moderate to strong earthquakes, reflecting its location within the active transition zone between the Pannonian Basin and the Dinaric Alps, where complex tectonics and heterogeneous geological conditions govern the local seismicity. Previous studies have shown that both regional seismotectonic setting and local to deep geological structures significantly influence seismic hazard and ground motion characteristics in the Banja Luka area [1]. The previous disasters led to large-scale reconstruction in Banja Luka and marked a turning point in the development of seismic design regulations, which have been progressively improved and are now further enhanced through the comparison of Eurocode-based seismic provisions. Within this regulatory framework, the assessment of structures of special importance such as hospitals, sport stadiums and schools requires an enhanced seismic performance criterion, with particular emphasis on detailed hazard analyses that explicitly involve the influence of local soil conditions. According to the IZIIS report [7] the central area of Banja Luka is classified as a location of particular importance for seismic hazard evaluation, owing to its urban significance and complex geological conditions. Detailed investigations of local site conditions were carried out using ambient vibration measurements with Tromino instrument on the soil surface (Fig. 1) for the identification of site-specific dynamic characteristics.

Figure 1. Ambient vibration measurement on the location in Banja Luka (report IZIIS 2009)

The results indicate a pronounced site effect, with a dynamic amplification factor of approximately 1.2, corresponding to a 20% increase in ground-motion amplitudes relative to reference rock conditions. To ensure a reliable seismic assessment of an important structure located at this site, the identified local soil effects are explicitly incorporated into the present analysis. To realistically capture the seismic demand associated with the Banja Luka earthquakes, a representative reinforced concrete frame as a part of a frame structure is analyzed using the recorded ground motion from the Banja Luka seismic event, complemented by artificial accelerogram generated in accordance with Eurocode 8 response spectra for different soil types. This combined approach enables a consistent evaluation of structural response under both site-specific and code-compliant seismic loading scenarios. Previous detailed analysis [2] have demonstrated the importance of the validity of the seismic analysis. In this study the seismic nonlinear frame analysis is conducted with OpenSees [6] where analysis show revealing results.

2. METHODOLOGY

2.1. SEISMIC INPUT SELECTION

The selection of seismic input motions was performed in accordance with the provisions of Eurocode 8, considering soil types A through E. For each soil category, spectrum-compatible artificial accelerograms were generated to match the target elastic response spectra corresponding to importance class IV structures. Additionally, the earthquake record from Banja Luka 1981 record has been used for the analysis to evaluate structural response under a realistic regional ground motion. The application of this historical record allows assessment of the influence of actual frequency content, duration, and amplitude modulation characteristics that may not be fully accounted for by smoothed design spectra. The local soil conditions have been adopted from the report of IZIIS [7] which indicates that the site conditions result in dynamic amplification of 1.2. The acceleration on a rock has been adopted as 0.15g as given in Bulajić et al. [1] which refers to the basic ground acceleration as it is in the level of engineering rock. The corresponding design spectra was then derived by incorporating the site amplification effects.

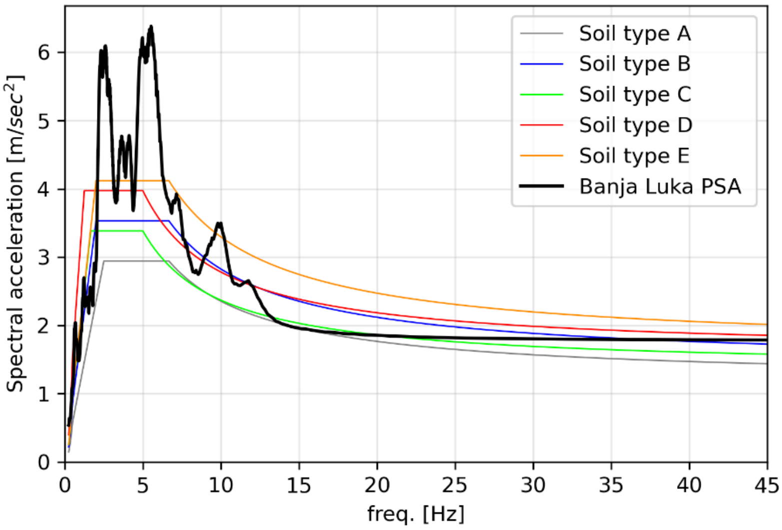

Figure 2. Comparison of Earthquake spectra according to importance class IV of Eurocode 8 (drawing by author).

As can be seen from Fig.2 the comparison of Eurocode 8-based design spectra and the response spectrum derived from the Banja Luka record reveals a similar overall spectral shape. The recorded spectrum can be broadly approximated as corresponding to soil type C; however, noticeable discrepancies in the spectral acceleration amplitudes are observed within the constant-acceleration (plateau) region. These differences in spectral ordinates, particularly in the natural frequency range governing the fundamental mode of the structure, indicate that the local earthquake exhibits distinct frequency content characteristics.

2.2. BANJA LUKA EARTHQUAKE RECORD

The selection of Banja Luka earthquake from 1981 year is based on Jordanovski et al., 1987. The earthquake that struck the Banja Luka region on 13 August 1981 occurred at approximately 02:58 local time and had a reported magnitude of M = 5.7. The epicenter was located in the wider Banja Luka area within the active seismogenic zone of the Dinarides and the event was of shallow crustal origin. The earthquake generated a moderate ground shaking in the city and surrounding area, causing limited to moderate damage, mainly to masonry buildings and non-ductile structural components, while remaining significantly weaker than the destructive 1969 Banja Luka earthquake. Importantly for engineering applications, the event was recorded by the local strong-motion network and accelerograms such as Banja Luka N–S component exhibit impulsive ground motion with relatively short significant duration and moderate peak ground acceleration as shown in Fig. 3.

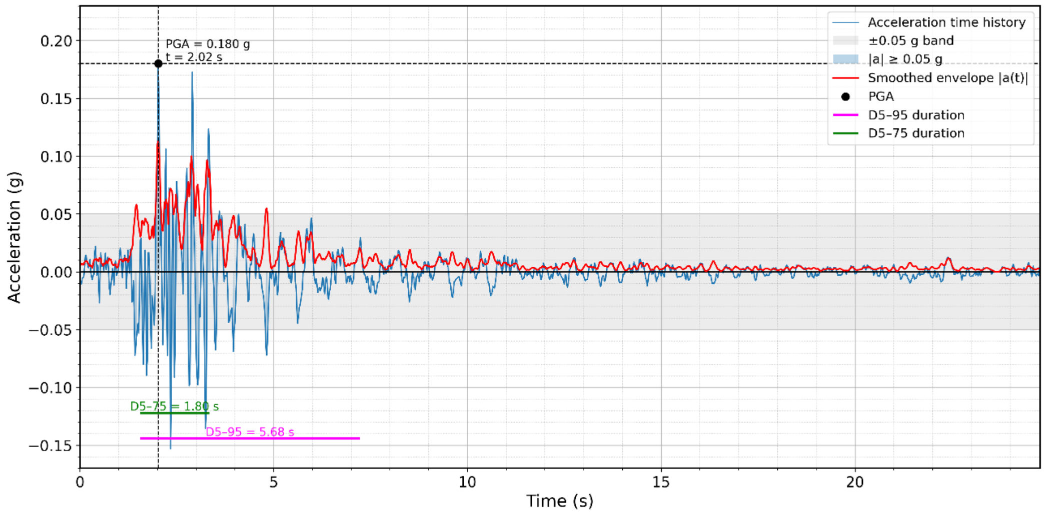

Figure 3. Acceleration time history of the Banja Luka earthquake 1981 (drawing by author).

The figure illustrates the main shock ground acceleration record, including the recorded acceleration time history (blue line), time intervals of absolute acceleration exceeding 0.05g (shaded regions), the smoothed acceleration envelope |a(t)| (red line), and the peak ground acceleration marked by a black dot, with a PGA value of 0.18g occurring at t = 2.02 s. The significant duration measures are also indicated, with D5–75 equal to 1.80 seconds and D5–95 equal to 5.68 seconds, shown by green and magenta bars, respectively. The acceleration record exhibits a distinct impulsive character, with the major concentration of the seismic energy released within the first 6 seconds of the ground shaking.

2.3. ARTIFICIAL EARTHQUAKE RECORDS FROM EUROCODE 8

In order to perform a complete analysis incorporating the effects of Eurocode 8 provisions, the spectrum for soil type C (corresponding to deep deposits of dense or medium-dense sand, gravel, or stiff clay) and for building of importance class IV, has been selected as the basis for generating artificial earthquake record. This synthetic ground motion has been generated using the software Code_Aster (Code-Aster, 2018), with particular attention to approximation and covering the "plateau" region (Fig. 4a).

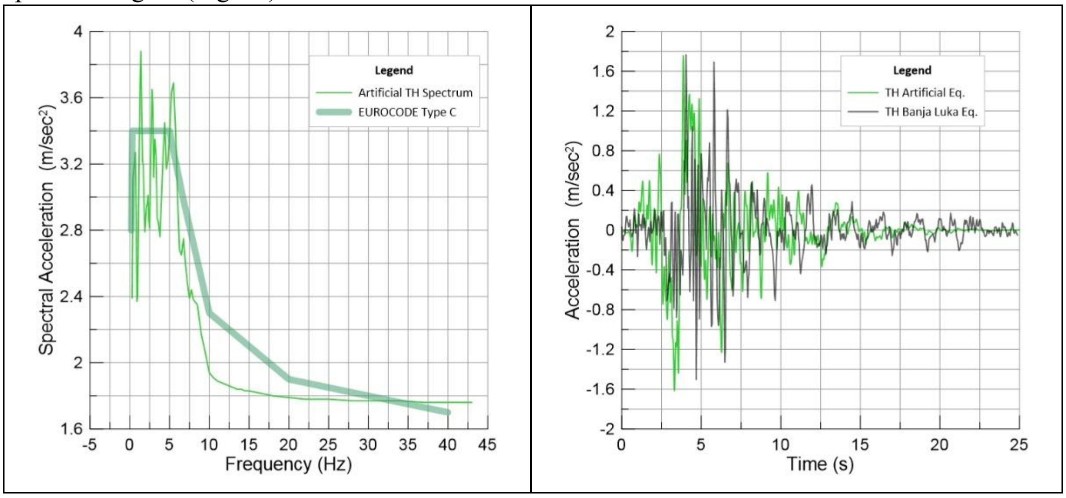

Figure 4. Comparison between Eurocode 8 spectrum (soil type C, importance class VI) and generated earthquake records: a) response spectra and b) acceleration time history (drawing by author).

The generated earthquakes maintain the same PGA, although the frequency content differs between records, which enables a more comprehensive assessment of the structural response across different seismic scenarios. This variability in frequency content, while preserving the target spectral shape and intensity, provides a realistic representation of potential seismic demands that comply with

Eurocode 8 requirements. Next, nonlinear structural analysis has been conducted to see the effects in the structural response.

3. STRUCTURAL RESPONSE

The structural system considered in this study is a three-storey, two-bay reinforced concrete (RC) moment-resisting frame designed to represent a typical medium-rise building in a moderate-to-high seismicity region. The interstorey height is 3.0 m, while the bay length is 5.0 m. The columns have square cross-section of 35×35 cm, reinforced with 4 bars of diameter 14 mm on each side. The beams have rectangular cross-sections of 35×40 cm, reinforced with 5 bars of diameter 14 mm as both top and bottom reinforcement. All structural members are modeled using nonlinear force-based beam-column elements with fiber-discretized cross-sections allowing for a realistic representation of material nonlinearity and the progressive development of plasticity. Concrete is modeled using a nonlinear constitutive relationship capable of representing confined (core) and unconfined (cover) behavior throughout setting the ultimate strain (0.01 for confined and 0.0035 for unconfined). The concrete compression strength has been adopted as 30 MPa. The reinforcing steel has been modeled with yield strength of 500 MPa using a nonlinear hysteretic model with isotropic hardening. The fiber discretization explicitly distinguishes between the core and the cover concrete, as well as longitudinal reinforcement layers. This modeling strategy enables realistic simulation of stiffness degradation, strength deterioration, and cyclic hysteretic behavior under seismic loading [3], [4]. The geometric configuration, node numbering, and element tagging of the analytical model are presented in Fig. 5. The base of the structure is assumed fixed. Gravity loads of 70 kN/m^1 are applied on every beam (consistent with a typical floor tributary area approach) prior to dynamic excitation to establish the initial stress state. The mass sources are derived from the applied gravity loads.

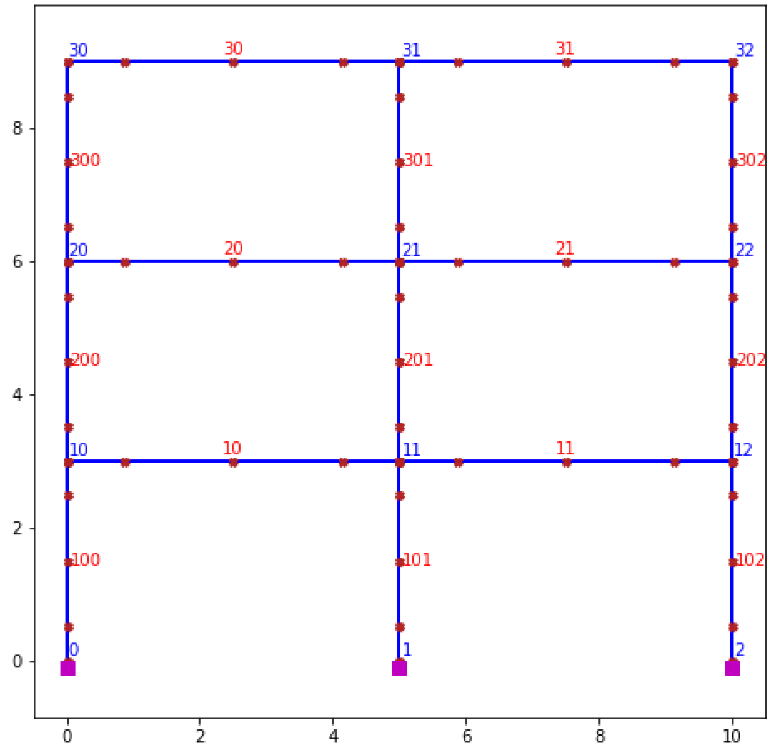

Figure 5. Numerical model of the structure in OpenSees (drawing by author).

The structural model is subjected to nonlinear time-history analyses applying two distinct categories of seismic input: (i) artificial ground motions generated to be compatible with the target Eurocode design spectrum, and (ii) the recorded accelerogram from the Banja Luka earthquake, as presented in Fig. 4. The artificial records ensure consistency with code-based spectral demands, while the historical Banja Luka record reflects realistic regional ground-motion characteristics, including amplitude modulation and frequency content specific to the site conditions.

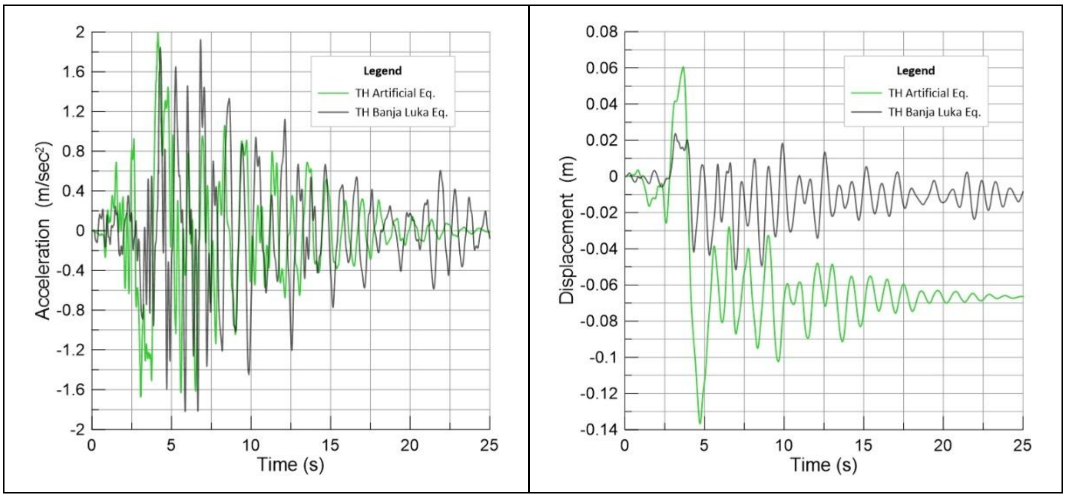

Figure 6. Comparison between Banja Luka and spectrum compatible earthquake records: a) absolute acceleration and b) relative displacement time histories at node 31 at top (drawing by author).

As shown in Fig. 6a, the acceleration time histories at the roof level exhibit a comparable overall pattern in terms of peak amplitudes and general oscillatory behavior. This similarity indicates that the initial stiffness and global dynamic properties of the frame dominate the short-period response. Since the absolute acceleration response is closely related to structural stiffness and mass distribution, the comparable peak values suggest that both ground motions activate similar elastic response mechanisms in the structure during the early stages of excitation.

However, a more pronounced difference is observed in the relative displacement response (Fig. 6b). The artificial, spectrum-compatible ground motion produces larger relative peak roof displacements compared to the recorded Banja Luka earthquake. This increase can be attributed to differences in spectral amplification within the period range corresponding to the fundamental mode of the frame. As previously shown in the spectral comparison (Fig. 4a), the artificial record imposes higher spectral ordinates in the vicinity of the structure's dominant period, resulting in increased lateral deformation demand.

The divergence in relative displacement response highlights the sensitivity of global deformation demands to the frequency content and duration characteristics of the input motion. While absolute acceleration response reflects stiffness-controlled behavior, relative displacement response is more strongly influenced by spectral compatibility and energy input within the fundamental period range. Given these differences in global deformation demand, further investigation of sectional nonlinear behavior is required. In particular, moment–curvature relationships at the upper end section of the top-storey column 301 are examined to assess the extent of material nonlinearity, stiffness degradation, and potential plastic hinge development under both excitation scenarios. The corresponding moment–curvature results for the two earthquake records are presented in Fig. 7.

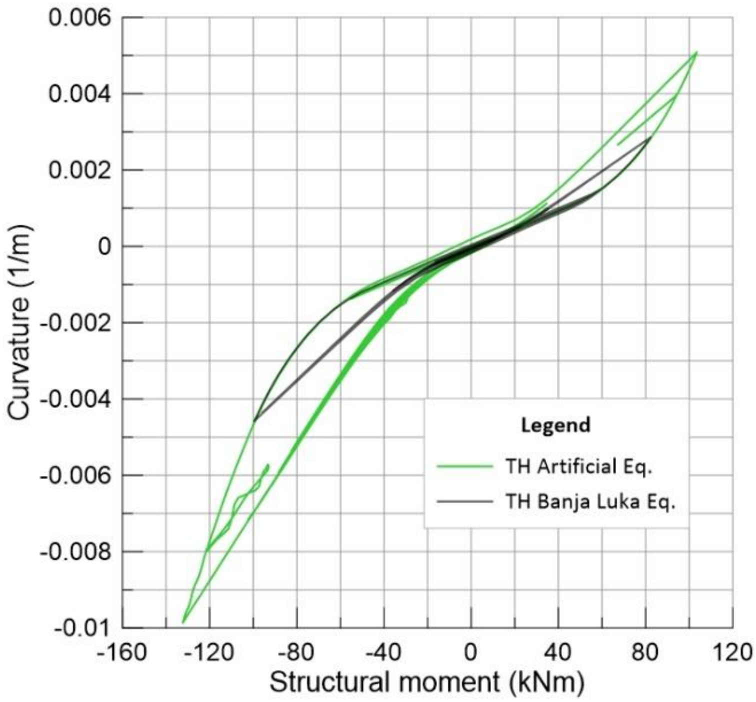

Figure 7. Moment curvature relationships at the upper end of column 301 (drawing by author).

As illustrated in Fig. 7, the moment–curvature response at the critical section of column 301 demonstrates a clear difference between the two seismic excitation scenarios. While the Banja Luka record induces a response that remains predominantly within the quasi-linear range with only modest curvature demands, the artificial spectrum-compatible ground motion drives the section into a significantly more nonlinear regime. The artificial earthquake, generated to match the Eurocode design spectrum, produces higher curvature demands and a more pronounced hysteretic response, indicating the formation and progression of plasticity in the section. This behavior is consistent with the previously observed increase in global displacement demand and reflects the higher spectral ordinates in the period range associated with the fundamental mode of the structure. The enhanced curvature demand confirms that the artificial record imposes a more severe deformation-controlled response, leading to stiffness degradation and increased hysteretic energy dissipation at the sectional level. The comparison between sectional moment–curvature behavior and the corresponding internal force distribution highlights the sensitivity of nonlinear response to the characteristics of the input motion. Even when peak accelerations appear comparable, differences in frequency content and spectral amplification can substantially alter deformation demands and plastic hinge development.

4. CONCLUSIONS

Advanced seismic capacity assessment of structures located in regions of moderate seismicity and complex geological conditions requires explicit consideration of site-specific ground-motion characteristics that extend beyond simplified code-based spectral representations. In this study, comprehensive nonlinear dynamic analyses were performed on a representative three-storey reinforced concrete frame using the OpenSees framework. The structural response has been evaluated under two categories of seismic input: the recorded 1981 Banja Luka earthquake and Eurocode 8 spectrum-compatible artificial accelerograms corresponding to soil types A through E. All earthquakes have been scaled to peak ground acceleration of 0.18g on the ground surface. The analyses revealed that frequency content characteristics and duration parameters of ground motions significantly influence structural response, even when peak ground accelerations are nominally identical. The 1981 Banja Luka earthquake record, while broadly consistent with Eurocode Type C spectrum, exhibited notable discrepancies in the constant-acceleration spectral range, producing structural demands that differed substantially from those predicted using code-based spectrum-compatible motions. These differences were particularly pronounced for structural components with natural periods in the range of 0.5–1.5 seconds, highlighting the limitations of peak-acceleration-based or smoothed-spectrum-based seismic design approaches.

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